Coordinated Control of Facts Devices in Electrical Power Systems

by

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COORDINATED CONTROL OF FACTS DEVICES IN ELECTRICAL POWER SYSTEMS

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CERTIFICATE

It is certified that this M Tech thesis work entitled **COORDINATED CONTROL OF FACTS DEVICES IN ELECTRICAL POWER SYSTEMS** *by* **Madduri Srinivasa Rao** *has been carried out under my supervision and this work has not been submitted elsewhere for a degree*

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ABSTRACT

This thesis presents small signal stability evaluation for a single machine infinite bus system with two parallel lines One line is series compensated by a Thyristor Controlled Series Capacitor (TCSC) and the other line is shunt compensated at the midpoint by a Static Var Compensator (SVC) Eigenvalue studies are performed to explore the possibilities of increasing the power transfer capability of different combinations of the study system Power System Stabilizer (PSS) when added to the excitation system damps the system oscillations for all the investigated system configurations TCSC when employed with Constant Current (CC) controller provides good system damping compared to TCSC with Constant Angle (CA) controller It is shown that a combination of TCSC with CC controller SVC and PSS results in a significant increase of power transfer capability of the system In addition such combination of FACTS devices ensures improved steady state voltage profile and simultaneous control of power sharing between two parallel lines of the study system

Contents

List of Figures

List of Tables

List of Principal Symbols And Abbreviations

D	Damping constant
H	Inertia constant
I i	Current
L	Inductance
C	Capacitance
R	Resistanceψδ°
ω	Angular velocity (rad/sec)
ω_0	Nominal system frequency (rad/sec)
B	susceptance
X	Reactance
SVC	Static Var Compensator
TCSC	Thyristor Controlled Series Capacitor
PSS	Power System Stabilizer
CA	Constant Angle
CC	Constant Current
TCR	Thyristor Controlled Reactor
DC	Direct Current
Ac	Alternating Current
AVR	Automatic Voltage Regulator
Line1	Refer Fig 2 1
Line2	Refer Fig 2 1
P_g	Generating Power

Chapter 1

INTRODUCTION

1.1 Introduction

To meet the load demand in a complex interconnected power system and to satisfy the stability and reliability criteria either the existing transmission lines must be utilized more effectively or new lines should be added to the system. Increased cost and right of the way (ROW) constraints restricts the installation of new lines. In practice ac transmission lines are under utilized. This has necessitated examination of strategies for better utilization of existing transmission system. Modern power electronic compensating and controlling systems are seen to be the means to achieve this goal.

1.2 Limitations to Power Flow

The causes which limit the power flow are

- Reduced voltage profiles with increase in power flow
- Insufficient compensation of series impedance and shunt admittance of the line
- Reduced stability margin with increase in power flow

The power flow over an ac line between buses 1 and 2 is given by

$$P = \frac{V_1 V}{X} Sin\delta$$

Where P is the power flow over the line 1 2 V_1 and V_2 are the voltage magnitudes at buses 1 and 2 X is the total series reactance of the line

δ is the phase angle difference between the two bus voltages

From the above equation the maximum power transfer capability of the line can be increased by

a) Increasing the voltage magnitudes (use of shunt capacitors SVC etc)

b) Decreasing the series impedance of the transmission line (use of series capacitors TCSC etc)

c) Increasing the angular difference between two bus voltages

CONSTRAINTS

1) Voltages should be within ±5% of nominal voltage
2) Steady state angular difference δ should not exceed 30° in order to have good transient stability margin

FACTS devices emerged to make the above conditions a b c possible

In transmission systems with multiple parallel paths between generation and load the actual major power paths can have an important impact on system operation during bothsteady state and transient conditions By employing variable series and shunt compensation using power electronic controllers power flow over an ac transmission line becomes flexible In other words such an ac transmission system becomes a flexible ac transmission system (FACTS)

1 3 FACTS

The IEEE definition for FACTS [3] is as follows Alternating current transmission systems incorporating power electronic based and other static controllers to enhance controllability and increase power transfer capability

This collective acronym FACTS has been used in recent years to describe a wide range of controllers many of them incorporating large power electronic converters which may at

present or in the future be used to increase the flexibility of power systems and thus make them more controllable. The two main objectives for the development of FACTS are

- To increase the power transfer capability of transmission networks and
- To provide direct control of power flow over designated transmission routes

The FACTS controllers are of two types: shunt connected controllers and series connected controllers.

1.3.1 Shunt Controllers

These provide reactive power compensation to control voltages at desired buses [11] and their location influences active power flow also. There are different types of shunt controllers as described below.

STATIC VAR COMPENSATOR (SVC)

Before static var compensators became widely available the adjustment of voltage in a transmission system other than at the terminals of a generator was possible only by mechanical switching of shunt elements or by providing synchronous condensers. The switching of shunt reactors or capacitors is comparatively crude causing abrupt voltage changes along with voltage and current transients. The SVC on the other hand provides rapid and fine control of voltage without moving parts. Early technologies (Early 1960s) included the saturated reactor which is not a power electronic system but since 1980s the thyristor has been the sole basis for shunt var compensating equipment.

The SVC uses conventional thyristors to achieve fast control of shunt connected capacitors and reactors.

The most important property of the SVC is its ability to maintain a substantially constant voltage at its terminals by continuous adjustment of the reactive power it exchanges with the power system. The control characteristic usually has a small positive slope to stabilize the operating point (which is defined as the intersection with system loadline) under contingencies the compensator provides reactive power support to quickly removes it should load be removed. Also using auxiliary control signals (like line current

line active and reactive powers etc) it is possible to improve system damping These auxiliary signals modulate the voltage level in accordance with the input signal

STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

It behaves as a solid state synchronous voltage source that is analogous to an ideal synchronous machine which generates a balanced set of sinusoidal voltages at the fundamental frequency with rapidly controllable magnitude and phase angle In addition to reactive power compensation with a suitable Direct Current (DC) energy storage device such as a battery or super conducting magnet this controller might in the future be used to handle peak power demand and prevent power interruptions

THYRISTOR CONTROLLED BRAKING RESISTOR (DYNAMIC BRAKE)

Braking resistors are designed to provide generator speed control by dissipating power in a power resistor Stability limits of synchronous generators can be improved by reducing the imbalance between machine mechanical power and electrical power during faults Thyristors controlled braking resistor can enhance the above function by using electronic rather than mechanical switching This will give faster response in both closing and reopening

1 3 2 Series Controllers

They are connected in series and used for active power flow control The different types of series controllers are

THYRISTOR CONTROLLED PHASE SHIFTING TRANSFORMERS

Since the power flow on transmission line is proportional to sine of the angle across the line utilizing a phase shifter to vary the angle across the line can control the steady state power flow Rapid phase angle control can be accomplished by replacing the mechanical tap changers by a thyristor switching network

THYRISTOR CONTROLLED SERIES COMPENSATOR (TCSC)

Adjusting the net series impedance of the line can control power transfer between two buses Conventional series compensation schemes switch capacitors to vary the level of compensation using mechanical devices such as power circuit breakers The limitations of mechanical switching devices force conventional series compensation schemes to be switched in relatively large discrete segments Furthermore the scheme is slow in terms of response time Thyristor controllers have the capability of rapid control of line compensation over a continuous range with resulting flexibility

TCSC controllers use Thyristor Controlled Reactor (TCR) in parallel with capacitor segments This combination allows capacitive reactance to be controlled smoothly over a wide range and switched upon command to a condition where the bi directional thyristor pairs conduct continuously resulting in insertion of an inductive reactance into the line TCSCs also allow higher levels of series compensation with significantly reduced risk of SSR interaction [15] operated in a vernier mode they take on an inductive resistive impedance characteristic at SSR frequencies thus acting to damp those oscillations TCSCs can be quickly switched to bypass mode (within ½ cycle) with the resulting inductive reactance effective in reducing short circuit current levels When conventional series capacitors are inserted in a line a DC offset exists in the capacitor voltage which dissipates slowly as a subsynchronous oscillation With a TCSC this post insertion DC offset can be eliminated within a few cycles by active control of bi directional thyristors TCSCs are also used for damping of small signal power oscillations in a tie line [16] Strategies for power oscillation damping with TCSC using local parameters such as line current magnitude is also reported in literature

1 4 POWER SYSTEM STABILIZER (PSS)

The Power System Stabilizer uses auxiliary stabilizing signals to control the excitation system so as to improve power system dynamic performance It is well established that fast acting exciters with high gain Automatic Voltage Regulator (AVR) can contribute to oscillatory instability in power systems This type of instability is characterized by low frequency (0 2 to 2 0 Hz) oscillations which can persist (or even

grow in magnitude). This type of instability can endanger system security and limit power transfer. The major factors that contribute to instability are

- Loading of the generator or the line
- Power transfer capability of transmission lines
- Power factor of the generator
- AVR gain

A cost efficient and satisfactory solution to the problem of oscillatory instability is to provide damping for generator rotor oscillations. Providing power system stabilizers (PSS) which are supplementary controllers in the excitation system conveniently does this. It can be generally said that need for PSS will be felt in situations when power has to be transmitted over long distances with weak AC ties. Commonly used input signals to PSS are shaft speed, terminal frequency and power. Power system dynamic performance is improved by the damping of system oscillations. This is a very effective method of enhancing small signal stability performance.

1.5 Objective and Philosophy

The main objective of this work is to investigate into various possibilities of achieving high power transfer with control over power flow on transmission line. As the existing lines are usually under utilized, it is desired to increase their power transfer capability. Traditionally it was not possible to control power flow over a line in a network. This is the reason why ac lines are called uncontrolled lines as far as power transfer is concerned. However, control can be achieved through series compensation which changes the effective series reactance of the line. If the power line is very long (greater than 500Km), terminating close to the characteristic impedance becomes imperative. To increase power levels that can be transmitted, either the characteristic impedance has to be reduced (by adding series compensation, TCSC) or the transmission voltages has to be increased. Reactive power transfer depends mainly on voltage magnitudes and to transmit it over long distances require a large voltage gradient. An increase in reactive power transfer causes an increase in active as well as reactive power losses. To overcome the above difficulties, in this work, static var compensator (SVC) is

used on Line 1 which meets the dynamic requirements of the reactive power and improves the steady state transient performance of the system

This work assumes that there exists a single machine infinite bus system with a single line (Line 1) compensated at the midpoint by a SVC Investigation has been carried out to explore the possibilities of doubling the existing power transfer which is 500MW A new line is connected in parallel with SVC line (Line 1) and to have control on power flow a TCSC is employed on Line 2 Both the lines are 600 Km long having natural load of 540 MW The contribution of PSS to damp the system oscillations has been studied

In the literature it is reported that the system comprising either of the two FACTS devices (SVC and TCSC) improves stability of the system and increases the power transfer capability of the system with control on power flow Besides this they offer number of advantages Then the thought of exploiting the advantages of these two FACTS devices motivated to do this thesis work Overall a coordinated control scheme is developed for the two FACTS devices and PSS in the study system

1 6 Organization of Chapters

Chapter2 describes the development of models for the synchronous generator excitation system mechanical system SVC and its controllers TCSC and its controllers and network The overall systems model formation for the single machine two line infinite bus system is described The model is linearized around an operating point for the purpose of performing small signal eigen value analysis

In Chapter3 studies are performed on single machine infinite bus system with two parallel lines with and without PSS This chapter further subdivided into two types Type I SVC and TCSC are not included in the study system Type II The study system comprises only SVC on Line 1 and no controllable device on Line 2 Studies are performed on the system with and without PSS and Line Current auxiliary controller

Chapter4 discusses the results obtained from the eigenvalue studies performed on SMIB system with two parallel lines comprising only TCSC on Line 2 and no dynamic device on Line 1 Studies carried out on the system without PSS and with constant angle (CA) and constant current (CC) controllers

Chapter5 discusses the results of the SMIB system with two parallel lines having SVC on Line1 and TCSC on Line2 Studies are performed for different combinations of SVC TCSC with Constant Angle (CA) and Constant Current (CC) controllers PSS and Line Current auxiliary controller of SVC

A brief review of the various contributions of this thesis and the scope for the future work has been consolidated in chapter 6

Chapter 2

SYSTEM MODELING

2 1 Introduction

In this chapter constituent subsystems of the study system are modeled and the power system is linearized around an operating point for the purpose of small signal analysis State space equations are developed for the overall system The overall model of the system is obtained by appropriately combining the above component models The system model thus obtained is nonlinear in nature

2 2 Study System

The study system depicted in Fig 2 1 An 1110 MVA synchronous generator is connected to an infinity bus via two 400 kV transmission lines One line is series compensated by Thyristor Controlled Series Capacitor (TCSC) and the other line is compensated at the midpoint by a Fixed Capacitor – Thyristor Controlled Reactor (FC TCR) type Static Var Compensator (SVC) Each line is of 600 Km long having nature load of 540 MW

2 3 Generator Model

The mathematical model of the synchronous generator used here is as proposed in [2] The schematic of the synchronous generator is shown in Fig 2 2 This shows three identical armature windings a b c and four rotor windings f h g and k f

coil represents the rotor field winding. The fictitious g coil represents the effect of eddy currents which circulate in the solid steel of rotor. The h and k coils represent the damper winding along d and q axis respectively. All windings except the field winding are short circuited as they are not connected to voltage sources.

The following assumptions are made:

(i) Fundamental frequency mmf distribution is considered in the air gap.
(ii) Subtransient saliency is neglected. Thus $X_d'' = X_q''$
(iii) Saturation is ignored.

Assumption (ii) and (iii) can be relaxed but is generally used to simplify the analysis. The effects of machine damping and prime mover dynamics are small and can also be neglected for simplicity.

The generator model described here can be further subdivided into

(a) stator circuits
(b) rotor circuits
(c) mechanical system
(d) excitation system

2.3.1 Stator Circuits

In this model the stator of synchronous generator is represented by a dependent current source I_S in parallel with an inductance L_S as shown in Fig 2.3. The dependent current source replaces the time varying coupling between the rotor windings and stator windings. It may be noted that I_S is a (3×1) vector and L_S is a (3×3) matrix. These are expressed as

$$I_S = [I_a \quad I_b \quad I_c]^t = I_d\, c + I_q\, s \qquad (2.1)$$

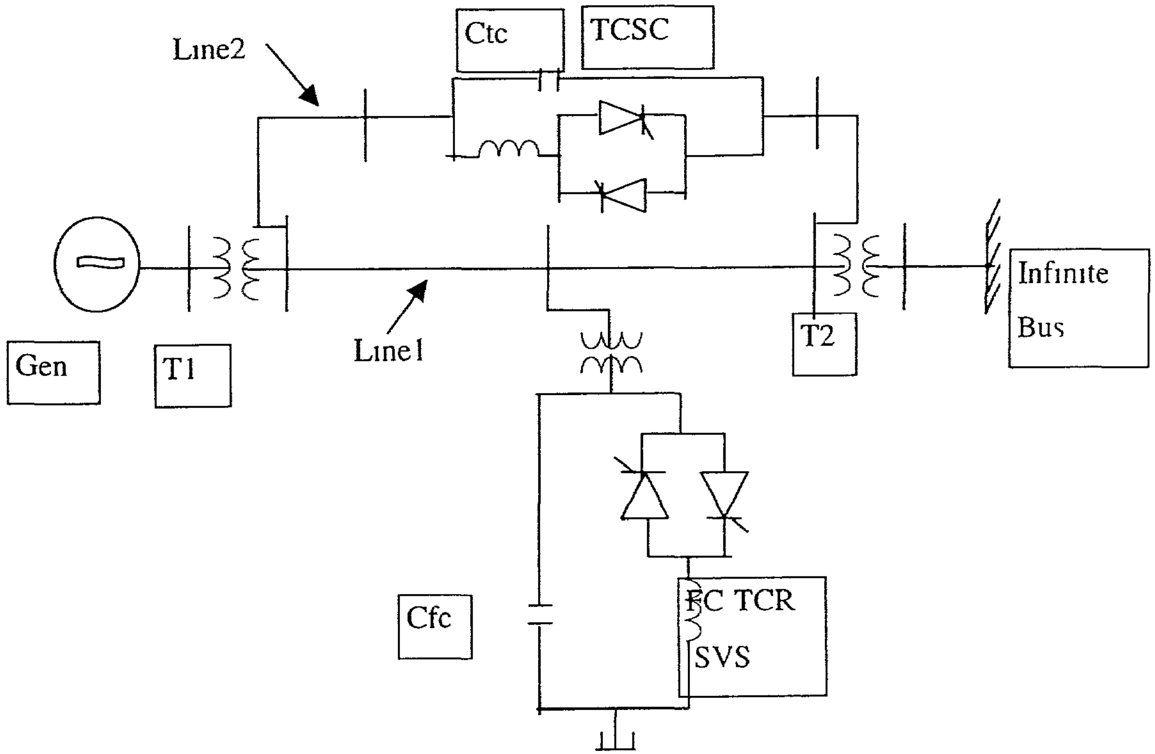


Fig 2 1 STUDY SYSTEM

where

$$c^t = \sqrt{(2/3)} \quad [\cos\theta \quad \cos(\theta - 2\pi/3) \quad \cos(\theta + 2\pi/3)]$$

$$s^t = \sqrt{(2/3)} \quad [\sin\theta \quad \sin(\theta - 2\pi/3) \quad \sin(\theta + 2\pi/3)]$$

I_d I_q are components of dependent current source along the d and q axis respectively θ is the rotor angle Subscript t indicates transpose

$$L_s = \frac{L_0}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} + \frac{2L_l}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2} & 1 & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{2} & 1 \end{bmatrix} \tag{2 2}$$

Such a representation of machine can handle both the symmetrical and unsymmetrical networks equally well If the external network connected to machine terminals is symmetrical as considered in this case a b c components can be transformed to α β o components The advantage of this transformation is that all the three α β o component models are uncoupled

Moreover α network is identical with β network and is the same as positive sequence network model

Equivalent source representation of the machine on α β o axes is derived in [4] and shown in Fig 2 4 The equivalent circuit consists of three meshes which are not mutually coupled R_s denotes the armature resistance The currents in the meshes correspond to α β o components of the armature currents The relationship between α β o components and the phase currents i_a i_b and i_c is given by

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{2}}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} \\ -\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{3}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_o \end{bmatrix} \tag{2 3}$$

The dependent current sources in α β frame of reference are defined as

$$I_\alpha = I_r \cos 6 + I_i \sin 6 \tag{2 4}$$

$$I_\beta = -I_r \sin 6 + I_i \cos 6 \tag{2 5}$$

2 3 2 Rotor Circuits

The rotor flux linkages are defined by

$$
\begin{aligned}
\Psi_f &= a_1\Psi_f + a\ \Psi_f + b_1 v_f + b\ i_f \\
\Psi_f &= a_3\Psi_f + a_4\Psi_f + b_3 i_f \\
\Psi_s &= a_5\Psi_s + a_6\Psi_k + b_5 i_f \\
\Psi_k &= a_7\Psi_s + a_8\Psi_k + b_6 i_f
\end{aligned} \tag{2 6}
$$

where v_f is the field excitation voltage

constants $a_1 - a_8$ $b_1 - b_6$ are defined in Appendix A The d and q components of the machine terminal current are defined by i_f i_f as

$$
\begin{aligned}
i_f &= \sqrt{\frac{2}{3}}\left[i\ \cos\theta + i_l \cos(\theta - \frac{2\pi}{3}) + i\ \cos(\theta + \frac{2\pi}{3}) \right] \\
i_f &= \sqrt{\frac{2}{3}}\left[i\ \sin\theta + i_l \sin(\theta - \frac{2\pi}{3}) + i\ \sin(\theta + \frac{2\pi}{3}) \right]
\end{aligned}
$$

It is noted that currents i_f and i_f are defined with respect to the machine reference frame However to have a common axis of representation with the ac network these currents are transformed to D Q frame of reference which is rotating at synchronous speed ω_0 The following transformation is employed

$$
\begin{bmatrix} i_f \\ i_f \end{bmatrix} = \begin{bmatrix} \cos\delta & -\sin\delta \\ \sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} i_D \\ i_Q \end{bmatrix} \tag{2 7}
$$

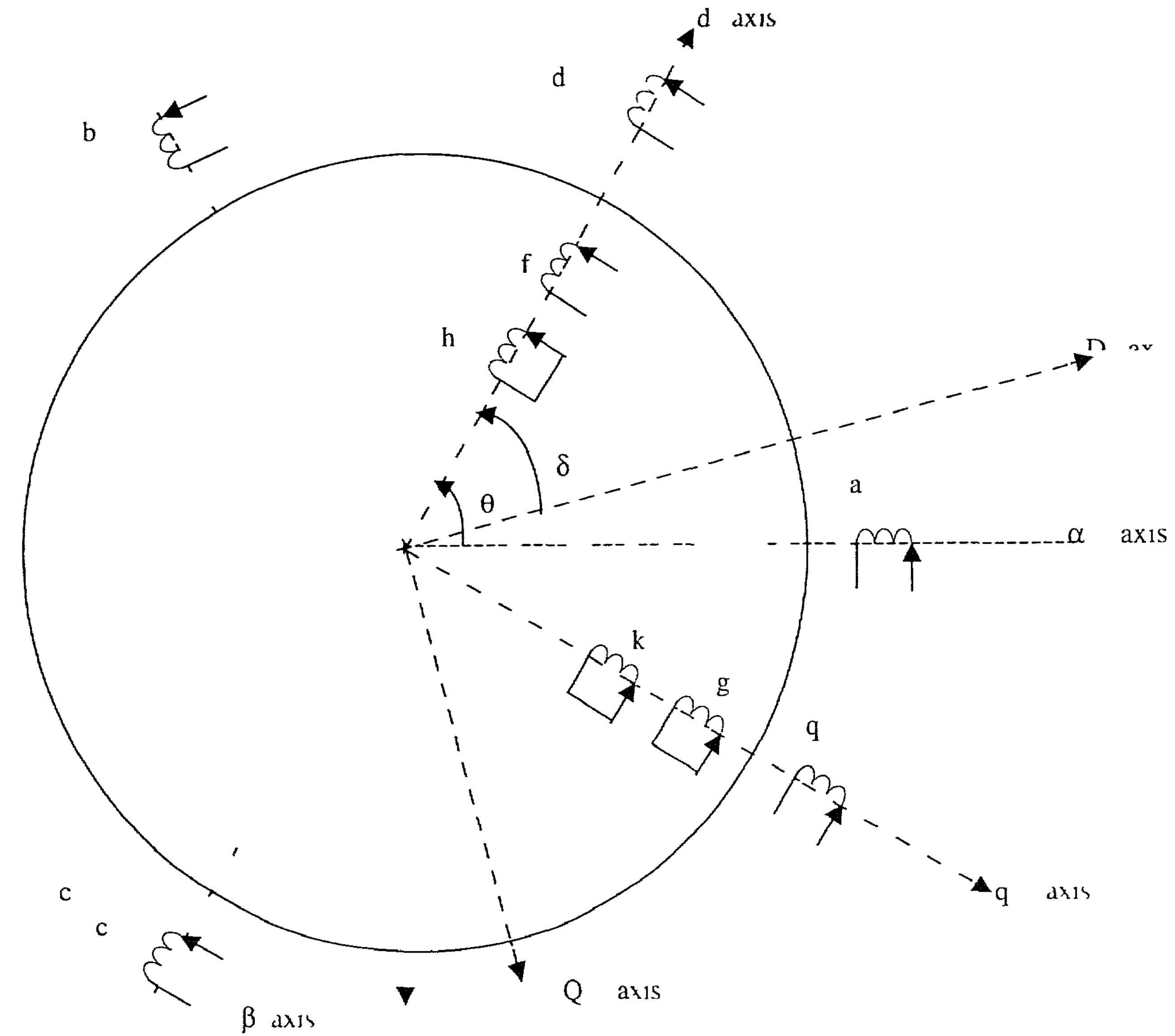


FIG 2 2 SCHEMATIC LAYOUT OF THE WINDINGS OF THE SYNCHRONOUS MACHINE AND THEIR TWO AXIS REPRESENTATION

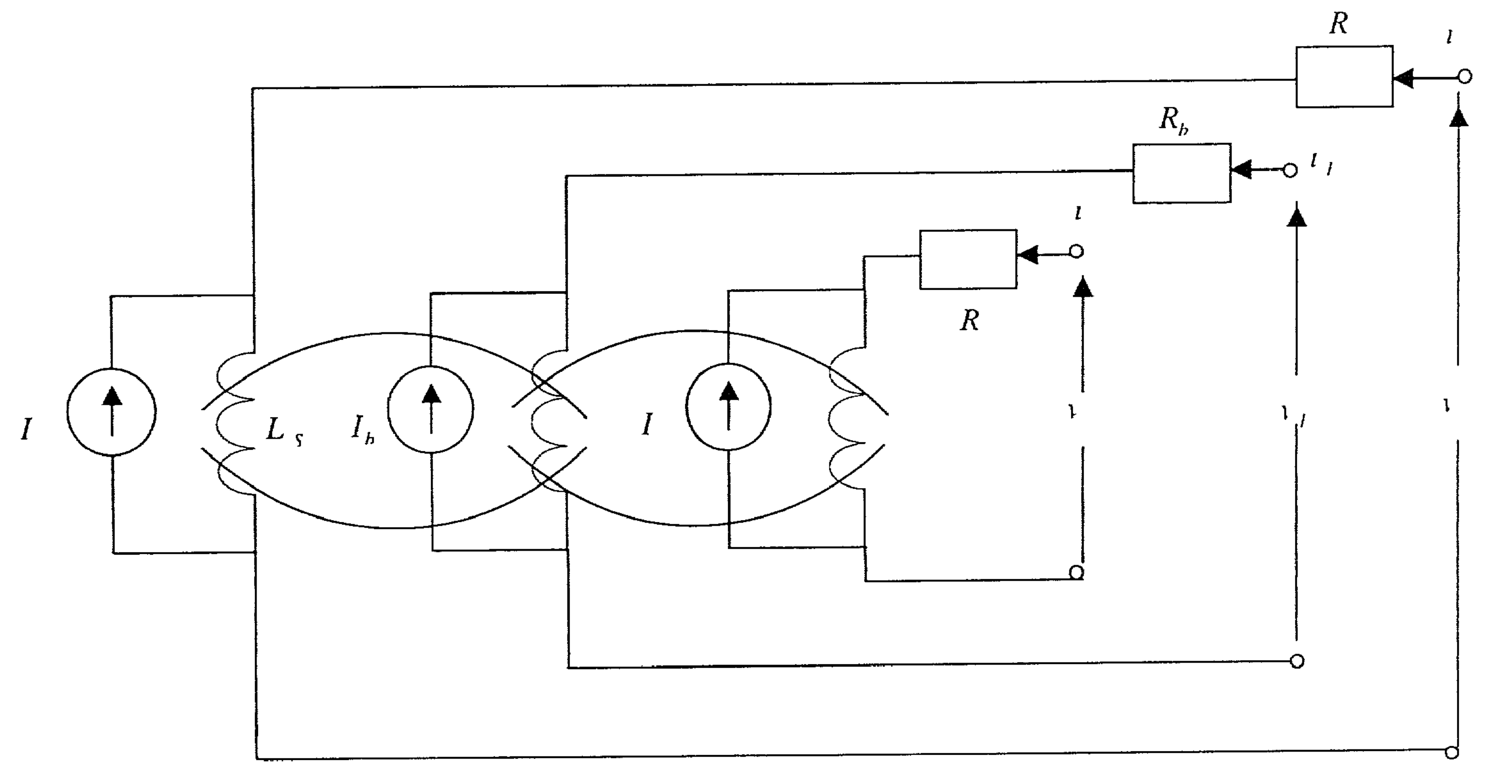
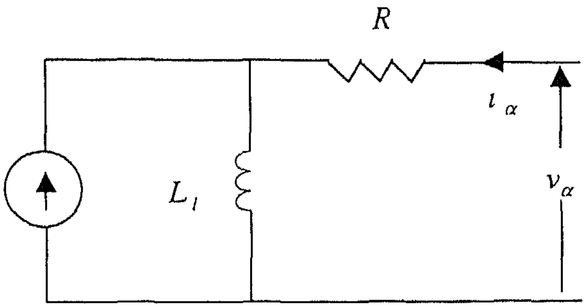
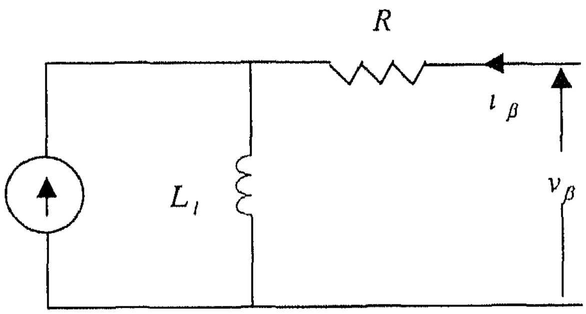


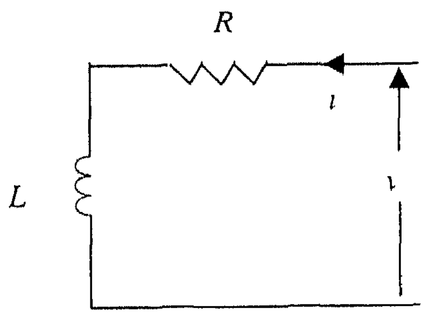
FIG 2 › CIRCUIT MODEL FOR THREE PHASE STATOR OF SYNCHRONOUS MACHINE



(a) α Axis representation



(b) β Axis representation



(c) o Axis representation

FIG 2 4 EQUIVALENT REPRESENTATION OF SYNCHRONOUS MACHINE ON α β 0 AXIS

where i_D, i_Q are the respective components of machine current along D and Q axis. δ is the angle by which d axis leads the D axis.

Substituting eqn (2.7) in eqn (2.6) and linearizing the resulting equation gives the state equation of the rotor circuits as

$$\dot{x}_R = A_R x_R + B_{R1} u_{R1} + B_{R2} u_{R2} + B_{R3} u_{R3} \qquad (2.8)$$

where

$$x_R = [\Delta\Psi_f \; \Delta\Psi_h \; \Delta\Psi_g \; \Delta\Psi_k]^t \qquad u_{R1} = [\Delta\delta \quad \Delta\omega]^t$$

$$u_{R2} = [\Delta v_f] \qquad u_{R3} = [\Delta i_D \quad \Delta i_Q]^t$$

Matrices A_R, B_{R1}, B_{R2} and B_{R3} are defined in Appendix B Sec B.1.

The output equation of the rotor subsystem is developed by utilizing the relationship between I_d, I_q and the rotor flux linkages as given in [2]

$$\begin{aligned} I_d &= c_1\Psi_f + c_2\Psi_h \\ I_q &= c_3\Psi_g + c_4\Psi_k \end{aligned} \qquad (2.9)$$

where constants $c_1 - c_4$ are defined in Appendix A.

I_d, I_q are now transformed to D–Q axis components I_D and I_Q respectively using the transformation

$$\begin{bmatrix} I_D \\ I_Q \end{bmatrix} = \begin{bmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} I_D \\ I_Q \end{bmatrix} \qquad (2.10)$$

The output equations are finally derived as eqns (B.6), (B.7) and given by

$$y_{R1} = C_{R1} x_R + D_{R1} u_{R1} \qquad (2.11)$$

$$y_R = C_R \, x_R + D_R \, u_{R1} + D_{R3} u_{R2} + D_{R4} u_{R3} \qquad (2.12)$$

where

$$y_{R1} = [\Delta \, I_D \quad \Delta \, I_Q]^t \; y_R = [\Delta I_D \quad \Delta I_Q]^t$$

Matrices C_{R1} C_R D_{R1} D_R D_{R3} and D_{R4} are defined in Appendix B Sec B 1

2 4 Mechanical System Model

The rotor angle is expressed as

$$6 = 6 \; + \delta \qquad (2.13)$$

where $6 = \omega \, t$

The nominal system frequency is given by

$$\omega \; = d6 \; / dt \qquad (2.14)$$

differentiating eqn 2 13 and using 2 14

$$\omega = \omega \; + d\delta / dt \qquad (2.15)$$

where $\omega = d6 / dt$

Linearizing eqn (2 15)

$$d\Delta\delta / dt = \Delta\omega \qquad (2.16)$$

The machine swing equation is given as

$$d\omega / dt = \frac{\omega}{2H}(-D\omega + T \; - T \;) \qquad (2.17)$$

where

H = inertia constant of generator

D = damping torque coefficient

T = mechanical torque

T_e = electrical torque

The electrical torque acting on the generator rotor as given in [] is expressed by

$$T_e = -x_d(i_d I_q + i_q I_d) \quad (2.18)$$

The currents i_d, i_q and I_d, I_q are transformed to D-Q reference frame using the relationship given in eqn. (2.7).

Substituting eqn. (2.18) in eqn (2.17) and linearizing we get

$$\dot{x}_M = A_M x_M + B_{M1} u_{M1} + B_M u_M \quad (2.19)$$

$$y_M = C_M x_M \quad (2.20)$$

where $x_M = [\Delta\delta \quad \Delta\omega]^t$ $\quad y_M = [\Delta\delta \quad \Delta\omega]^t$

$u_{M1} = [\Delta I_D \quad \Delta I_Q]^t$ $\quad u_M = [\Delta i_D \quad \Delta i_Q]^t$

It is noted that when turbine – governor dynamics is neglected

$\Delta T_m = 0$

$\Delta i_D, \Delta i_Q$ are the incremental D-Q axis components of the current entering generator terminals in the system.

$\Delta I_D, \Delta I_Q$ are the incremental D-Q axis components of the dependent current source.

A_M, B_{M1}, B_M, B_{M3} and C_M are defined in Appendix B Sec B.2.

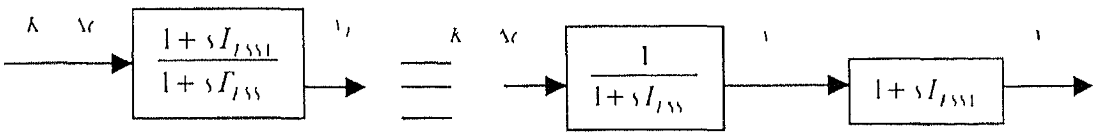
2.5 Modeling of Excitation System

The excitation system is represented by the IEEE Type 1 model as shown in fig 2.5. The Power System Stabilizer (PSS) is included in the system. v_t is the generator terminal

voltage and S_E is the saturation function. The excitation system including the PSS is described by the following equations.

Power System Stabilizer (PSS)

The model considered for PSS is a simple lead lag circuit and gain K_{STAB}. Washout stage is not modeled as the studies in this work do not require it. Generator rotor angular velocity is taken as the input signal to PSS. The PSS is modeled as given below.



$$\dot{v}_{s1} = -\frac{v_{s1}}{T} + \frac{K_{stab}}{T}\Delta\omega \tag{2.21}$$

$$v_{PSS} = \left(1-\frac{T_1}{T}\right)v_{s1} + K_{stab}\left(\frac{T_1}{T}\right)\Delta\omega \tag{2.22}$$

$$\dot{v}_f = -\frac{(K_E+S_E)}{T_E}v_f + \frac{1}{T_E}v_r \tag{2.23}$$

$$\dot{v}_r = -\frac{K_F(K_E+S_E)}{T_E T_F}v_f - \frac{v_r}{T_F} + \frac{K_F}{T_E T_F}v_r \tag{2.24}$$

$$\dot{v}_a = -\frac{K_A}{T_A}v_r - \frac{1}{T_A}v_a - \frac{K_A}{T_A}v_t + \frac{K_A}{T_A}V_{REF} + \frac{K_A}{T_A}\left(1-\frac{T_1}{T}\right)v_{s1} + \frac{K_A}{T_A}K_{stab}\frac{T_1}{T}\Delta\omega \tag{2.25}$$

The state and output equations of the linearized system are respectively derived as eqns (B.13) and (B.14) and expressed as

$$\dot{x}_E = A_E x_E + B_{E1}u_{E1} + B_E u_E \tag{2.26}$$

$$y_E = C_E x_E \tag{2.27}$$

$$x_E = [\Delta v_f, \Delta v_r, \Delta v_a, \Delta v_{s1}]^T \qquad u_{E1} = \Delta v_t \qquad u_E = [\Delta\delta \quad \Delta\omega]$$

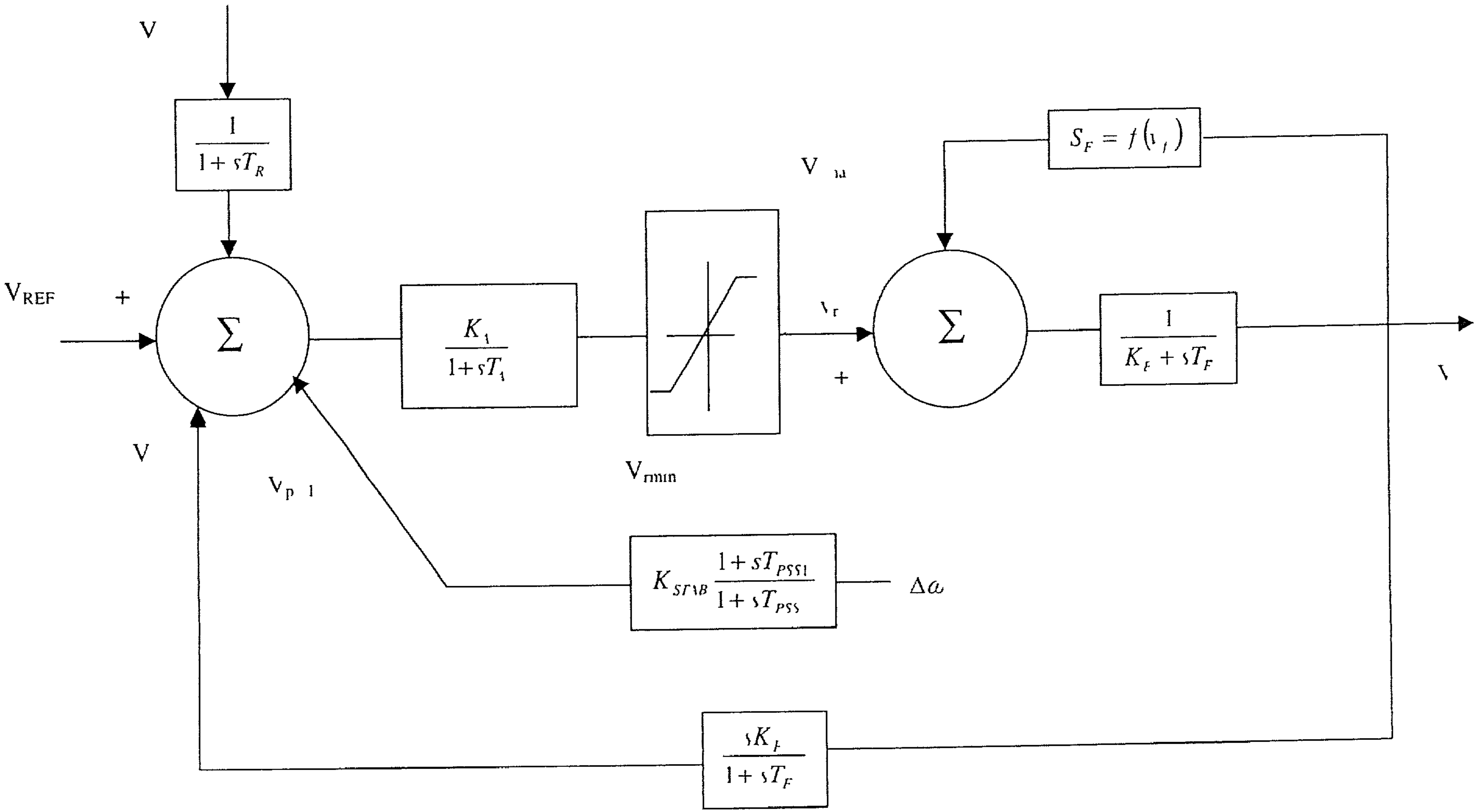


Fig 2 5 BLOCK DIAGRAM OF IEEE TYPE1 EXCITATION SYSTEM INCLUDING POWER SYSTEM STABILIZER

2.6 Network Model

The network model includes the model of generator stator, two transformers, two transmission lines, Static Var Compensator (SVC) and Thyristor Controlled Series Capacitor (TCSC) and the infinite bus. Both the transformers are represented by their leakage reactances. The magnetizing current is neglected. Each half of Line1 on either side of SVS is represented by a single equivalent π circuit and that of Line2 is represented by L only (assuming that line capacitances are compensated by the Shunt Reactors). The infinite bus is represented as a constant voltage and constant frequency source.

Fig. 2.6 depicts the α axis representation of the study system shown in Fig. 2.1. I_α is the α component of dependent current source as described in the stator circuit model of synchronous machine. The current entering the generator is represented by i_α. The terminal voltage at infinite bus is indicated by $v_{1\alpha}$. The leakage inductance of the transformer at generator end is denoted by L_{T1} whereas L_t represents the leakage inductance of the transformer connected to infinite bus.

The equations for the symmetrical network expressed on α axis are written as

$$\frac{di_1}{dt} = \frac{v}{L_t} - \frac{v_1}{L_t} \tag{2.28}$$

$$\frac{di_{2\alpha}}{dt} = -\frac{R}{L} i_{2\alpha} + \frac{v_{3\alpha}}{L} - \frac{v_{2\alpha}}{L} \tag{2.29}$$

$$\frac{di_{4\alpha}}{dt} = -\frac{R}{L} i_{4\alpha} + \frac{v_{4\alpha}}{L} - \frac{v_{3\alpha}}{L} \tag{2.30}$$

$$\frac{di_\alpha}{dt} = -\frac{R_1}{L_1} i_\alpha + \frac{v_{4\alpha}}{L_1} - \frac{L_l}{L_1}\frac{dI}{dt} \tag{2.31}$$

$$\frac{di_{\alpha}}{dt} = \frac{v_{4\alpha}}{2L} - \frac{v_{2\alpha}}{2L} - \frac{v_{t\alpha}}{2L} \tag{2.32}$$

$$\frac{dv_{\alpha}}{dt} = \frac{i_{2\alpha}}{C} + \frac{i_{\alpha}}{C} - \frac{i_{1\alpha}}{C} \tag{2.33}$$

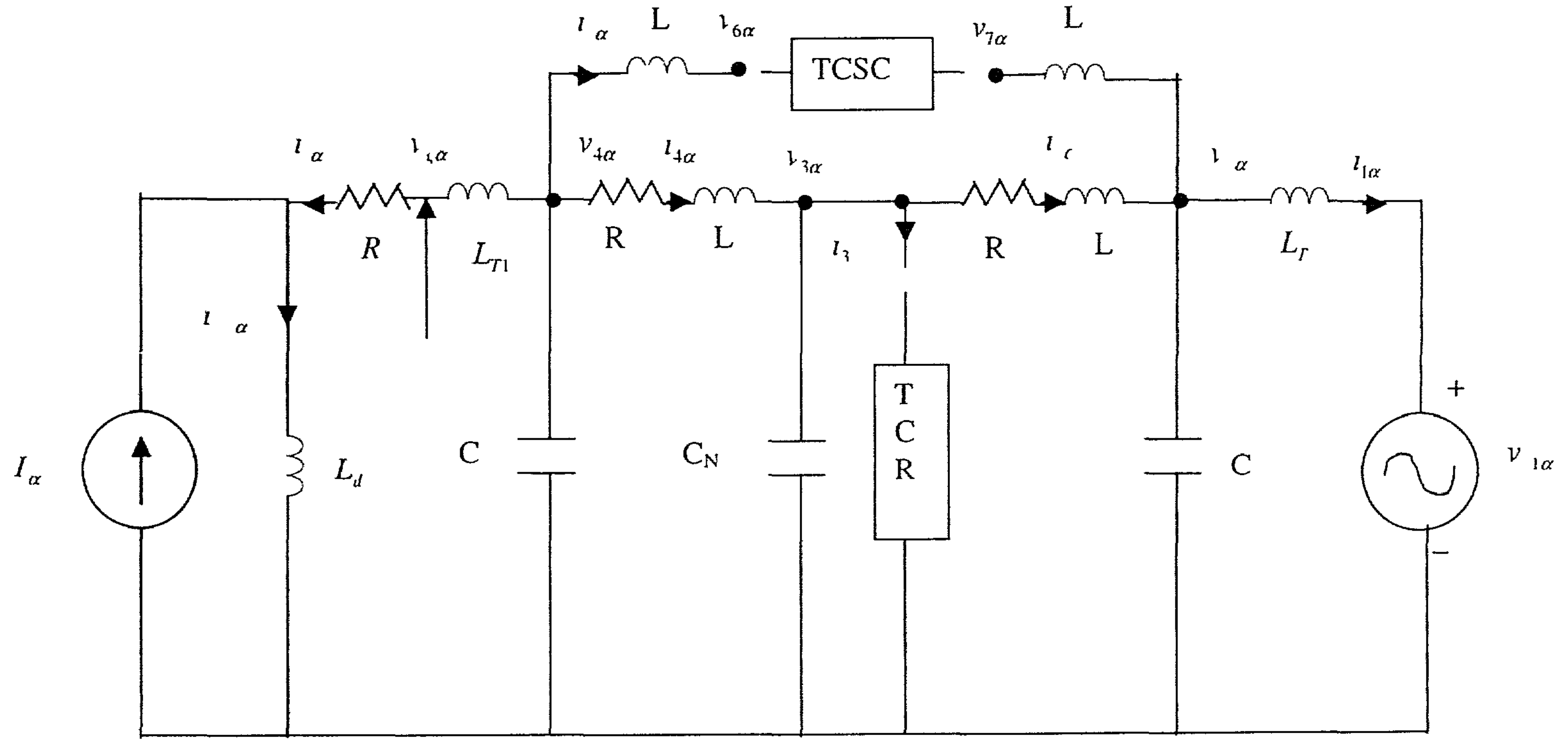


FIG 2 6 TRANSMISSION NETWORK ON α AXIS FOR THE STUDY SYSTEM (PSS SVC WITH LINE CURRENT AUXILIARY CONTROLLER AND TCSC WITH CA(or CC) CONTROLLER

$$\frac{dv_3}{dt} = \frac{i_4}{C} - \frac{i_{3\alpha}}{C} - \frac{i}{C} \qquad (2.34)$$

$$\frac{dv_4}{dt} = -\frac{i_{4\alpha}}{C} - \frac{i_\alpha}{C} - \frac{i_\alpha}{C} \qquad (2.35)$$

where $\quad L_1 = L_{T1} + L_l \qquad\qquad C = 2C + C_{FC}$

The above equations can be rewritten in matrix form as

$$x_\alpha = S_1 x + S\, i_3 + S_3 I + S_4 v_{1\alpha} + S_5 v \qquad (2.36)$$

where $\qquad x_\alpha = [i_{1\alpha}\ \ i_{\alpha}\ \ i_{4\alpha}\ \ i_\alpha\ \ i_\alpha\ \ v_\alpha\ \ v_{3\alpha}\ \ v_{4\alpha}]^t$

Matrices S_1, S, S_3, S_4, S_5 are defined in Appendix B secB4

Similarly the equations for the β network are

$$x_\beta = S_1 x_\beta + S_2 i_{3\beta} + S_3 I_\beta + S_4 v_{1\beta} + S_5 v_{\beta} \qquad (2.37)$$

where $\qquad x_\beta = [i_{1\beta}\ \ i_{\beta}\ \ i_{4\beta}\ \ i_\beta\ \ i_\beta\ \ v_\beta\ \ v_{3\beta}\ \ v_{4\beta}]^t$

Since the variables x_α, x_β are sinusoidal quantities in steady state they result in a time varying system In order to reduce the overall system to a time invariant one it is necessary to transform the variables by a D Q transformation on synchronously rotating reference frame The D Q components of the variable x are related to α β components by the following transformation

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta\ I & \sin\theta\ I \\ -\sin\theta\ I & \cos\theta\ I \end{bmatrix} \begin{bmatrix} x_D \\ x_Q \end{bmatrix} \qquad (2.38)$$

where $\qquad x_D = [i_{1D}\ \ i_{2D}\ \ i_{4D}\ \ i_D\ \ i_D\ \ v_D\ \ v_{3D}\ \ v_{4D}]$

$$x_Q=[i_{1Q}\ \ i_{Q}\ \ i_{4Q}\ \ i_{Q}\ \ i_{Q}\ \ v_{Q}\ \ v_{Q}\ \ v_{4Q}]$$

I is an identity matrix of proper dimension δ is the angle by which D axis leads α axis

Equations (2 36) and (2 37) are transformed to D – Q frame of reference using eqn (2 38) and then linearized It is noted that $\Delta v_{1D} = \Delta v_{1Q} = 0$

The state equation of the network model is finally obtained as

$$\dot{x}_N = A_N x_N + B_{N1} u_{N1} + B_{N} u_{N} + B_{N3} u_{N3} + B_{N4} u_{N4} \qquad (2\ 39)$$

where $x_N = [x_D \ \ x_Q]^t$ $u_{N1} = [\Delta i_{3D} \ \ \Delta i_{3Q}]^t$ $u_{N2} = [\Delta I_D \ \ \Delta I_Q]$

$$u_{N3} = \left[\Delta I_D \ \ \Delta I_Q\right]^t \quad u_{N4} = [\Delta v_{D} \ \ \Delta v_{D}]^t$$

Matrices A_N B_{N1} B_{N2} B_{N3} B_{N4} are defined in Appendix B Sec B 4

The voltage and current at generator terminals SVS bus voltags and the input current to the TCSC (current flowing through the Line2) constitutes the output of network model The corresponding network output equations are derived is eqns (B22 B 26) and given by

$$y_{N1} = C_{N1} x_N + D_{N1} u_{N1} + D_{N2} u_{N} + D_{N3} u_{N3} + D_{N4} u_{N4} \qquad (2\ 40)$$

$$y_{N2} = C_{N} x_N \qquad (2\ 41)$$

$$y_{N3} = C_{N3} x_N \qquad (2\ 42)$$

$$y_{N4} = C_{N4} x_N \qquad (2\ 43)$$

$$y_{N5} = C_{N5} x_N \qquad (2\ 44)$$

where

$$y_{N1} = \Delta v_{k} \quad y_{N2} = [\Delta i_{D} \quad \Delta i_{Q}] \quad y_{N3} = [\Delta v_{3D} \quad \Delta v_{3Q}] \quad y_{N4} = [\Delta i_{D} \quad \Delta i_{Q}]$$

$$y_{N5} = [\Delta i_{4D} \quad \Delta i_{4Q}]^{t}$$

Matrix C_{N1} C_{N} C_{N3} C_{N4} C_{N5} D_{N1} D_{N} D_{N3} and D_{N4} are defined in Appendix B Sec B 4

2.7 Detailed SVS Model

This section describes the modeling of SVC voltage control system and modeling of Line Current Auxiliary Controller of SVC. TCR transients are also modeled. The delays associated with SVS controller and measurement unit is also incorporated.

SVC is a dynamic reactive power device which provides rapid and continuously controllable lagging and leading MVARs. Variation of reactive power can be achieved through both the active and passive control.

2.7.1 Operating Characteristic of SVC

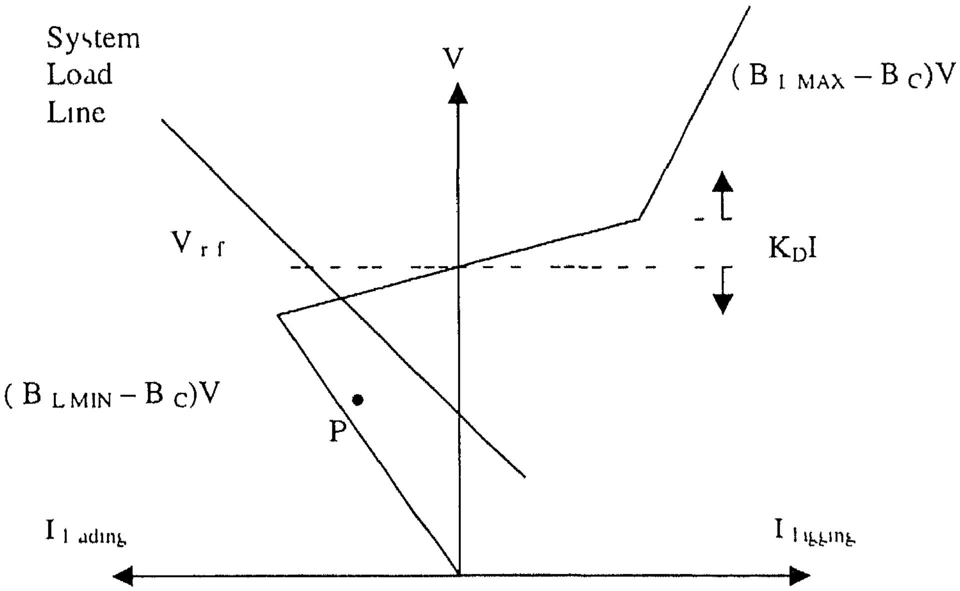
Fig 2.7 shows the steady state control characteristic of an SVC which represents the relationship between SVC current (or reactive power output) and the bus voltage. The steady state operating point is established at the intersection of the control characteristic with the system load line. For small deviations in the bus voltage around the controller set point V_{f} the SVC current is regulated within the control range to provide inductive compensation for voltage rises and capacitive compensation for voltage drops. Thus SVC maintains the terminal voltage at the preset reference V_{f}. Large changes in the bus voltage force the SVC beyond its control range. For severe undervoltages the SVC gets transformed into an equivalent fixed capacitor having susceptance $B_{LMIN} - B_{C}$ while for large overvoltages it reduces to an equivalent shunt reactor of susceptance $B_{LMAX} - B_{C}$

The slope of the control characteristic essentially represents a compromise between SVC rating and the voltage stabilizing requirement. It also improves the current sharing between the SVCs operating in parallel. The slope of the control characteristic is typically chosen in the range of 1-10 %.

2.7.2 Modeling of SVC Voltage Controller including Line Current Auxiliary Controller

A small signal model of a general SVC control system is depicted in Fig 2.8. The terminal voltage perturbation ΔV and the SVC incremental current

weighted by the factor K_D representing current droop are fed to the reference junction T_M represents the measurement time constant which for simplicity is assumed to be equal for both voltage and current measurements The voltage regulator is assumed to be a proportional integral (PI) controller Thyristor control action is represented by an average dead time T_D and a firing delay time T_S The variation in TCR susceptance is represented by ΔB



P operating point

B_C = SVC capacitive susceptance

B_L = SVC inductive susceptance

FIG 2 7 STEADY STATE CONTROL CHARACTERISTIC OF SVC

The α β axis currents entering TCR from the network are expressed as

$$L_S \frac{d i_{3\alpha}}{dt} + R_S i_{3\alpha} = v_{3\alpha} \tag{2.45}$$

$$L_S \frac{d i_{3\beta}}{dt} + R_S i_{3\beta} = v_{3\beta}$$

where L_S, R_S represent the inductance and resistance of the TCR respectively

Transforming equation (2.45) to D Q frame of reference using equation (2.38) and linearizing gives

$$\begin{bmatrix} \Delta i_{3D} \\ \Delta i_{3Q} \end{bmatrix} = \omega_0 \begin{bmatrix} -\frac{1}{Q} & -1 \\ 1 & -\frac{1}{Q} \end{bmatrix} \begin{bmatrix} \Delta i_{3D} \\ \Delta i_{3Q} \end{bmatrix} + \omega_0 B_0 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta v_{3D} \\ \Delta v_{3Q} \end{bmatrix} + \omega_0 \begin{bmatrix} v_{3D0} \\ v_{3Q0} \end{bmatrix} \Delta B \tag{2.46}$$

where Q = Quality Factor of TCR $= \frac{\omega_0 L_S}{R_S}$ $\qquad B = \frac{1}{\omega_0 L_S}$

2.7.3 Line Current Auxiliary Controller

Fig 2.9 depicts the block diagram of an SVC control system involving feedback of a general auxiliary signal u_C through a controller transfer function G(s). In this analysis the perturbation in SVC reference voltage V_r is assumed to be zero. The magnitude of transmission line current i_4 entering SVC bus from the generator end as shown in Fig 2.6 is given by

$$i_4 = \sqrt{i_{4D} + i_{4Q}} \tag{2.47}$$

where i_{4D}, i_{4Q} are the components of line current i_4 along D Q axis respectively

The auxiliary control signal chosen in this case is the perturbation in line current magnitude Δi_4 which is obtained by linearizing eqn (2.47)

$$\Delta i_4 = \frac{i_{4D0}}{i_{40}}\Delta i_{4D} + \frac{i_{4Q0}}{i_{40}}\Delta i_{4Q} \qquad (2\ 48)$$

The auxiliary controller is assumed to be a simple first order transfer function for this auxiliary signal

$$G(s) = \frac{\Delta v_I}{\Delta i_4} = K \quad (\frac{1 + sT_{\ 1}}{1 + sT_{\ }})$$

The equivalent representation of the controller is shown in the fig 2 10

$$v_1 = -\frac{v_1}{T_{\ }} + \frac{K}{T_a}\Delta i_4 \qquad (2\ 49)$$

$$\Delta v_F = (1 - \frac{T_{\ 1}}{T})v_1 + \frac{T_{\ 1}}{T}K \quad \Delta i_4 \qquad (2\ 50)$$

The following equations can be written for SVS control system including Line Current auxiliary controller

$$z_1 = \Delta V_{rf} + (1 - \frac{T_{\ 1}}{T})v_1 + \frac{T_{\ 1}}{T_i}K \quad \Delta i_4 - z \qquad (2\ 51)$$

where $\Delta V_{\ f}$ is the reference voltage perturbation

$$\Delta v_3 - K_D \Delta i_3 = z \ + T_M\ z \qquad (2\ 52)$$

where Δv_3 Δi_3 are the incremental magnitudes of SVS bus voltage and TCR current

$$z_2 = \frac{1}{T_M}(\Delta v_3 - K_D\ \Delta i_3) - \frac{1}{T_M}z \qquad (2\ 53)$$

$$-K_I z_1 - K_I z_1 = z_3 + T_S z_3 \qquad (2\ 54)$$

Substituting eqn (2 51) in eqn (2 54) gives

$$z_3 = -\frac{K_I}{T_S}z_1 + \frac{K_I}{T_S}z \ - \frac{1}{T_S}z_3 - \frac{K_P}{T_S}\Delta V_{\ f} - \frac{K_P}{T_S}(1 - \frac{T_{\ 1}}{T})v_1 - \frac{K_P}{T_S}\frac{T_{\ 1}}{T}K \quad \Delta i_4 \qquad (2\ 55)$$

$$ {}_{3} = \Delta B + T_D \Delta \dot{B} \tag{2.56}$$

or

$$\Delta \dot{B} = \frac{1}{T_D} {}_{3} - \frac{1}{T_D} \Delta B \tag{2.57}$$

The magnitude of TCR current is given by

$$i_3 = \sqrt{(i_{3D} + i_{3Q})} \tag{2.58}$$

Linearizing eqn (2.58)

$$\Delta i_3 = \frac{i_{3D0}}{i_{30}} \Delta i_{3D} + \frac{i_{3Q0}}{i_{30}} \Delta i_{3Q} \tag{2.59}$$

The SVS bus voltage v_3 is also expressed in terms of its D Q axis components as

$$v_3 = \sqrt{(v_{3D} + v_{3Q}^{2})} \tag{2.60}$$

Linearizing equation (2.60) gives

$$\Delta v_3 = \frac{v_{3D0}}{v_{30}} \Delta v_{3D} + \frac{v_{3Q0}}{v_{30}} \Delta v_{3Q} \tag{2.61}$$

Eqns (2.59) (2.61) are substituted in eqn (2.53) to give the state equation corresponding to z

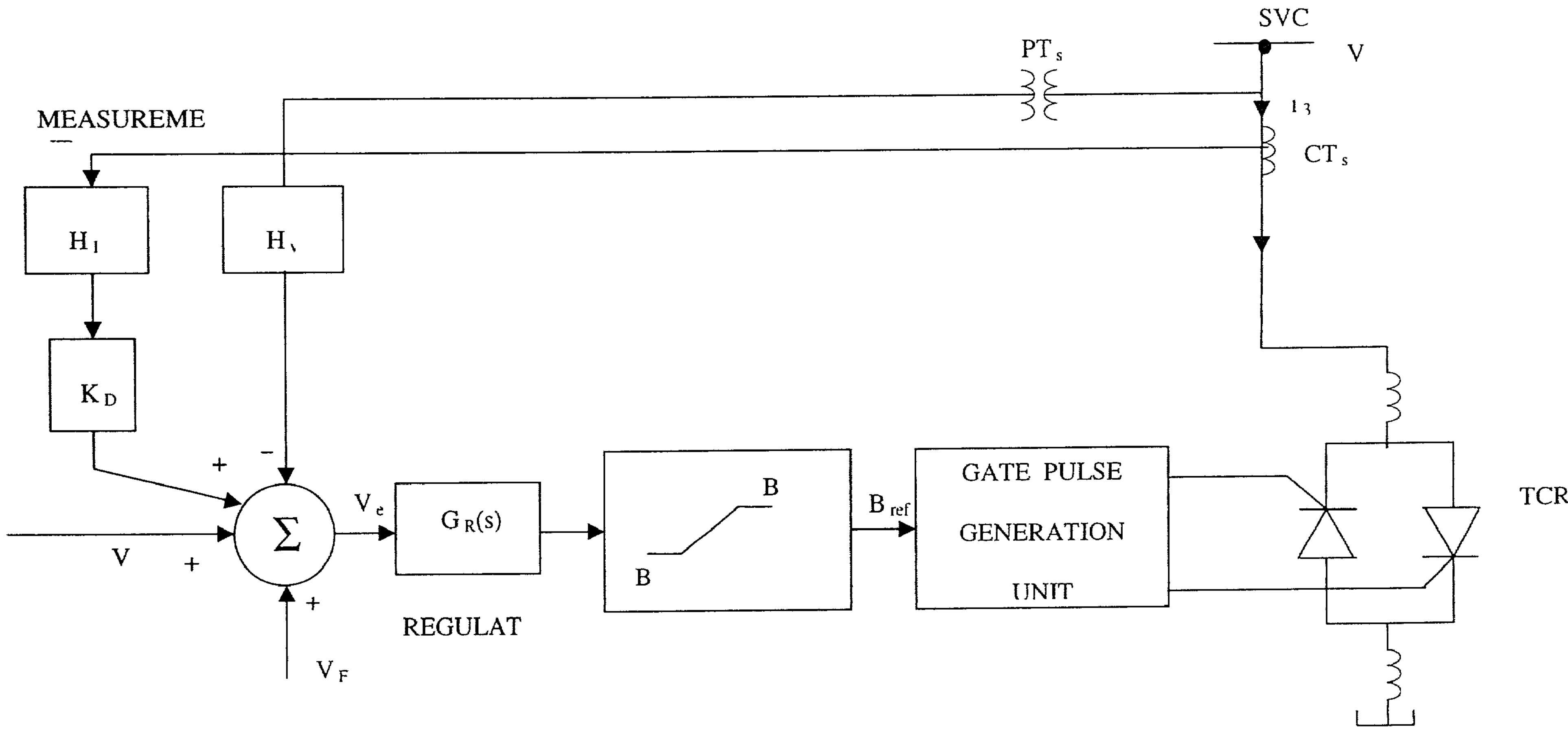


FIG 2 8 GENERAL CONTROL SYSTEM BLOCK DIAGRAM FOR THYRISTORIZED SVC

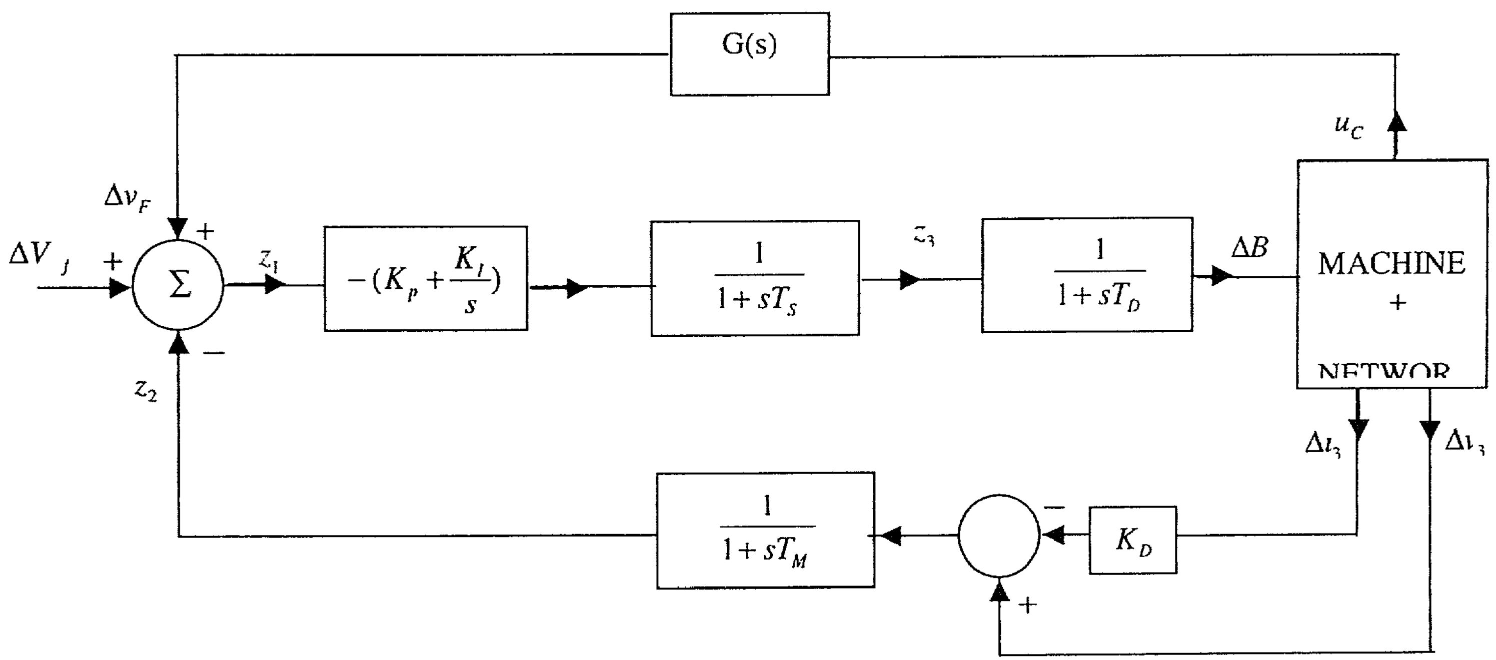
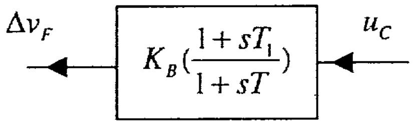
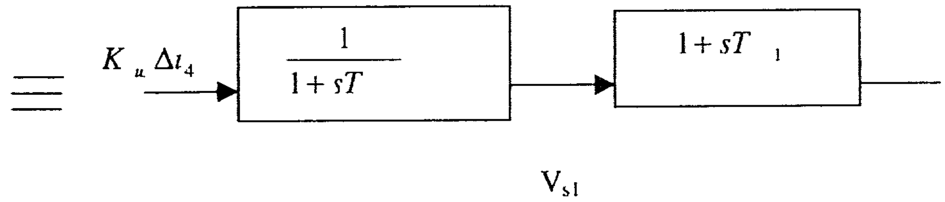


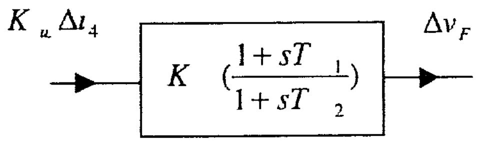
FIG 2 9 SVC CONTROL SYSTEM WITH AUXILIARY FEEDBACK



General First Order Auxiliary Controller



Equivalent representation of Aux Cont



Line Current Auxiliary Controller

Fig 2 10 Line Current Auxiliary Controller

The state and output equations of the SVC model can then be written as

$$\dot{x}_s = A_s x_s + B_{s1} u_{s1} + B_{s2} u_{s2} + B_{s3} u_{s3} \tag{2.62}$$

$$y_s = C_s x_s + D_s u_{s1} \tag{2.63}$$

where
$$x_s = [\Delta i_{3D} \quad \Delta i_{3Q} \quad z_1 \quad z_2 \quad z_3 \quad \Delta B \quad v_1]^t$$

$$u_{s1} = [\Delta v_{3D} \quad \Delta v_{3D}]$$

$$u_{s2} = [\Delta i_{4D} \quad \Delta i_{4Q}], \quad u_{s3} = \Delta V_f, \qquad y_s = [\Delta i_{3D} \quad \Delta i_{3Q}]^t$$

Matrices A_s, B_{s1}, B_{s2}, B_{s3}, C_s and D_s are defined in Appendix B Sec B.5

2.7.4 Choice of SVC Rating

The dynamic range of SVC is chosen on the basis of reactive power requirement at the SVC bus to control voltage under steady state conditions. This information is obtained from load flow studies which in addition provide the voltage magnitudes and phase angles at various buses needed to compute the initial conditions in the system. The SVC bus is assumed to be a PV bus with zero power injection (SVC losses are neglected).

Load flow is then conducted and SVC bus reactive power is computed for varying generator power outputs. For the study system(SVC and TCSC) it is seen that as the generator real power increases from 100 MW to 1200 MW the SVC reactive power output varies from 206 MVA inductive to 193 MVA capacitive. Hence the dynamic range of SVC is chosen as 200 MVA inductive to 200 MVA capacitive. It is important to note that as the SVC configuration is FC TCR the reactor is rated larger than the fixed capacitance in order to provide net lagging VARs The slope of the steady state V I characteristic of SVC which is defined on nominal voltage base and the larger of the two reactive ratings is taken as 3 % at 200 MVA capacitive reactive power output of SVC

2.8 Modeling of Thyristor Controlled Series Capacitor (TCSC)

This section presents the modeling of TCSC Constant Angle Controller and constant Current controller. State space equations are developed and linearized in the neighborhood of an operating point for the purpose of dynamic stability analysis.

2.8.1 Operation of TCSC

Taking the voltage across the capacitor of TCSC as reference, the firing angle can be varied from 90 degrees to 180°.

When Thyristor valves are fired at 90°, Full conduction of Thyristor takes place resulting in to continuous and sinusoidal current flow in the reactor. TCSC will be operating in the inductive mode with minimum inductive reactance effectively.

For a firing angle of 180° thyristor valves are blocked. Here the TCSC reactance is same as that of the capacitive reactance of the TCSC.

As the firing angle increases from 90, vernier control of TCSC occurs. With the increase in firing angle the net reactance of TCSC (inductive) increases up to resonance. Usually resonance occurs around 120° depending on L & C parameters of TCSC. During resonance, the impedance offered by TCSC is very high. Further increment in firing angle causes the net reactance of TCSC to become capacitive and it reduces with increase in firing angle and attains minimum at 180° firing angle.

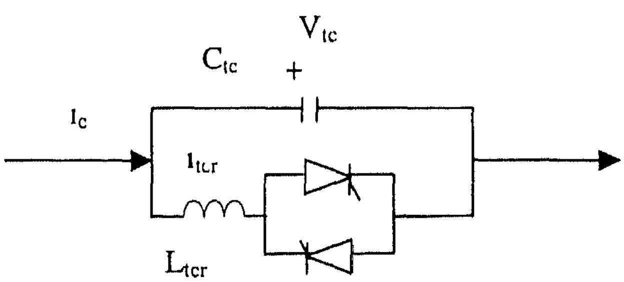


Fig 2.11 TCSC Model

TCSC model comprises of a capacitor connected in parallel to thyristor controlled reactor (TCR) as shown in figure 2.11. The net reactance of TCSC can be varied from

inductive to capacitive by changing the conduction period in the TCR path TCSC is operated only in the capacitor mode and the inductive mode is used during fault conditions TCSC is connected in series with a transmission line

2 8 2 Criterion for Design of L and C values of TCSC

The value of capacitance is fixed depending on the required level of compensation The value of L should be chosen such that their resonance frequency will be around 2 2 5 times nominal frequency The chosen value should be such that the steady state operating point falls in the middle of capacitive region of TCSC The advantage of this is that during disturbances there will be enough margin on either side Also to avoid resonance it is necessary to operate the TCSC such that XTCSC/XC is not more than a limit (between 2 and 3)

2 8 3 Modeling of open loop TCSC

From fig 2 11 The α β axis currents entering TCR from the network are expressed as

$$L_t \frac{d i_{t\alpha}}{dt} + R_t \, i_{t\alpha} = v_{t\alpha} \qquad (2\ 64)$$

$$L_t \frac{d i_{t\beta}}{dt} + R_t \, i_{t\beta} = v_{t\beta}$$

where L_t R_t represent the inductance and resistance of the TCR respectively

Transforming equation (2 64) to D Q frame of reference using equation (2 38) and linearizing gives

$$\begin{bmatrix} \Delta \dot{i}_{tD} \\ \Delta \dot{i}_{tQ} \end{bmatrix} = \begin{bmatrix} -\frac{R_t}{L} & -\omega \\ \omega & -\frac{R_t}{L} \end{bmatrix} \begin{bmatrix} \Delta i_{tD} \\ \Delta i_{tQ} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} \Delta v_{tD} \\ \Delta v_{tQ} \end{bmatrix} + \begin{bmatrix} \frac{-\omega_0}{(\omega_0 L_t)} v_{tD0} \\ \frac{-\omega_0}{(\omega_0 L_t)} v_{tQ0} \end{bmatrix} \Delta X \qquad (2\ 65)$$

The X of TCR of TCSC can be related to X_{TCSC} (assumed to be positive in the capacitive region) as

$$x_{TCSC} = \frac{x_C\, x}{x_C - x} \qquad (2\ 66)$$

linearizing the above eqn (2 66) gives

$$\Delta x = (1 - \omega\ L_t\ C_t\ )\ \Delta x_{TCSC} \qquad (2\ 67)$$

X_{TCSC} = effective reactance of TCSC

X = output reactance of TCR

X_C = capacitive reactace of TCSC capacitor(C_{tc})

From fig 2 11 The α β axis eqns for the capacitor(Ctc) are expressed as

$$C_t \frac{d v_{t\alpha}}{dt} = i_{\alpha} - i_{t\alpha} \qquad (2\ 68)$$

$$C_t \frac{d v_{t\beta}}{dt} = i_{\beta} - i_{t\beta}$$

Linearizing the eqn (2 68) after transforming it to D Q frame of reference using equation (2 38) and using eqn (2 67) and rearranging the eqns (2 65) and (2 68) gives the final state space eqn for the TCSC as

$$\begin{bmatrix} \Delta i_{tD} \\ \Delta v_{tD} \\ \Delta i_{tQ} \\ \Delta v_{tQ} \end{bmatrix} = \begin{bmatrix} -\frac{R_t}{L_t} & \frac{1}{L_t} & -\omega & 0 \\ -\frac{1}{C_t} & 0 & 0 & -\omega \\ \omega & 0 & -\frac{R_t}{L_t} & \frac{1}{L_t} \\ 0 & \omega & -\frac{1}{C} & 0 \end{bmatrix} \begin{bmatrix} \Delta i_{tD} \\ \Delta v_{tD} \\ \Delta i_{tQ} \\ \Delta v_{tQ} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{1}{C_t} & 0 \\ 0 & 0 \\ 0 & \frac{1}{C_t} \end{bmatrix} \begin{bmatrix} \Delta i_D \\ \Delta i_Q \end{bmatrix} +$$

$$+ \begin{bmatrix} \frac{-\omega\ (1-\omega\ L_t\ C_t\ )\ v_{tD}}{(\omega\ L_t\ )} \\ 0 \\ \frac{-\omega\ (1-\omega\ L_t\ C_t\ )^{2} v_{tQ}}{(\omega\ L_t\ )} \\ 0 \end{bmatrix} [\Delta x_{TCSC}] \qquad (2\ 69)$$

the values of L_t C_t R_t are given in the Appendix C

2 8 4 Modeling of Controller for TCSC

The simplest type of power scheduling control adjusts the reactance order (or setpoint) to meet the required steady state power flow requirements of the transmission network To achieve this a closed loop current control (Constant Angle control and Constant Current control) is used in which the line current is compared to a reference current (which may be derived from the required power level)

This section describes the modeling of Constant Angle (CA) and Constant Current (CC) controllers [17]

In CA control the angular difference across the line is kept constant Assuming the voltage magnitudes at the two ends of the line are regulated maintaining constant angle is equivalent to maintaining constant voltage difference between two ends of the line This type of controller during a transient enables the line in which TCSC is situated to carry the required power so as to maintain the power flow in parallel paths constant

Both CC (Constant Current) and CA controllers used are of PI type The steady state control characteristics of both CC and CA control are shown in fig 2 12 (a) and (b) respectively Assuming V_{TCSC} to be positive in the capacitive region the characteristics have three segments OA AB and BC The control range is AB OA and BC correspond to the limits on X_{TCSC} In Fig 2 12 (b) the control range AB is derived by the equation

$V_{tc} = I_c X_{Lin}\ V_{OC}$

Where I is the magnitude of the line current X_{Line} is the net line reactance (including the fixed series compensation if any) V_{OC} is the constant(regulated) voltage drop across the line (including TCSC) Thus the slope of the line AB is X_{Li} OA and BC corresponds to the lower and higher limits on TCSC respectively

Fig 2 13 shows the general block diagram of TCSC For small signal stability studies it is not necessary to model the gate pulse unit and the generation of gate pulses The delay in firing angle is modelled by first order lag as shown in fig 2 13

The block diagram of constant current (CC) or constant angle (CA) controller is shown in fig 2 14 T_{mea} is the time constant of first order low pass filter associated with the measurement of line current I_c

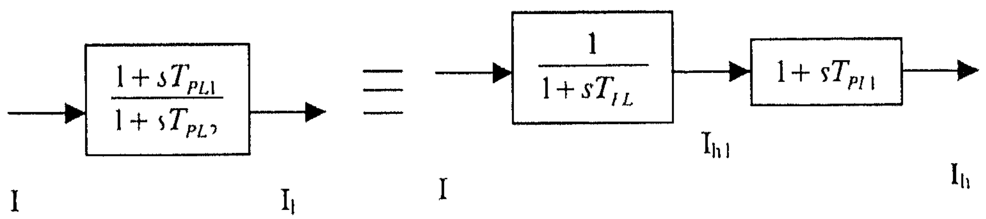
and TCSC voltage V_t. S=0 for CC control and S=$\frac{1}{X_t}$ for CA control. K_I and T_I are proportional gain and time constants respectively. T_{PL1} and T_{PL2} are time constants of lead lag compensation circuit. I_c and V_{tc} are input line current to TCSC and voltage across TCSC capacitor.

In CA control I_{ref} is actually the voltage reference divided by X_{Ln}. PI controller is used with a phase lead circuit. In case of CA control positive error signal implies the net voltage drop in the line is less than the reference and X_{TCSC} (assumed to be positive in capacitive region) is to be reduced. For CC control, if error is positive, the has to increase X_{TCSC} to raise the line current to reduce the error.

Constant Angle (CA) Controller

The controller block diagram is shown in the fig. 2.14, in which S=$\frac{1}{X_I}$. The following eqns. can be written for TCSC with CA control.

The lead lag circuit is modeled as follows

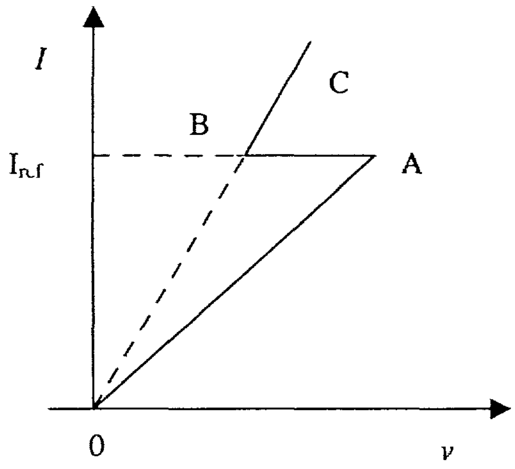


$$\dot{I}_{l1} = -\frac{I_{h1}}{T_{PL2}} + \frac{1}{T_{PL2}}(\Delta I_f - I) \tag{2.70}$$

$$I_k = I_{l1}\left(1-\frac{T_{PL1}}{T_{ll}}\right)K_{lt} + K_{lt}\frac{T_{PL1}}{T_{ll}}(\Delta I_f - I) \tag{2.71}$$

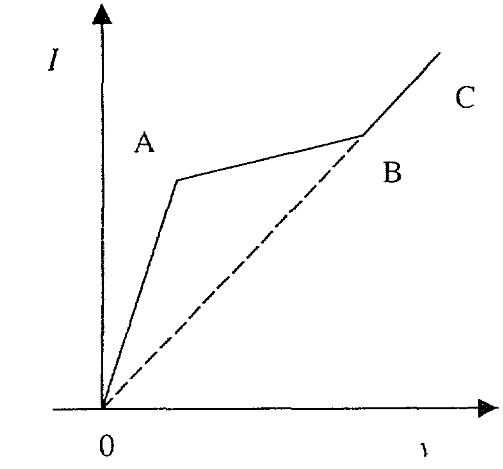
$$\dot{I}_l = -\frac{I_l}{T_l} + \frac{K_p}{T_l}I_{h1}\left(1-\frac{T_{PL1}}{T_{ll}}\right) + \frac{K_l}{T_l}\frac{T_{PL1}}{T_{PL}}(\Delta I_f - I) \tag{2.72}$$

$$\Delta\dot{x}_{TCSC} = -\frac{\Delta x_{TCSC}}{T_{TCSC}} + \frac{I_k + I_l}{T_{TCSC}} \tag{2.73}$$



(a) CC CONTROL

Fig 2 12 Control Characteristics



(b) CA CONTROL

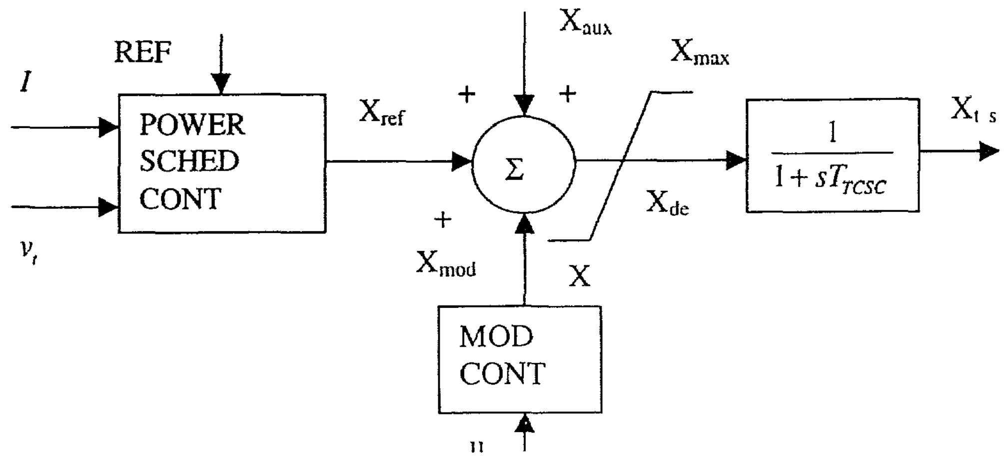


Fig 2 13 Block diagram of TCSC

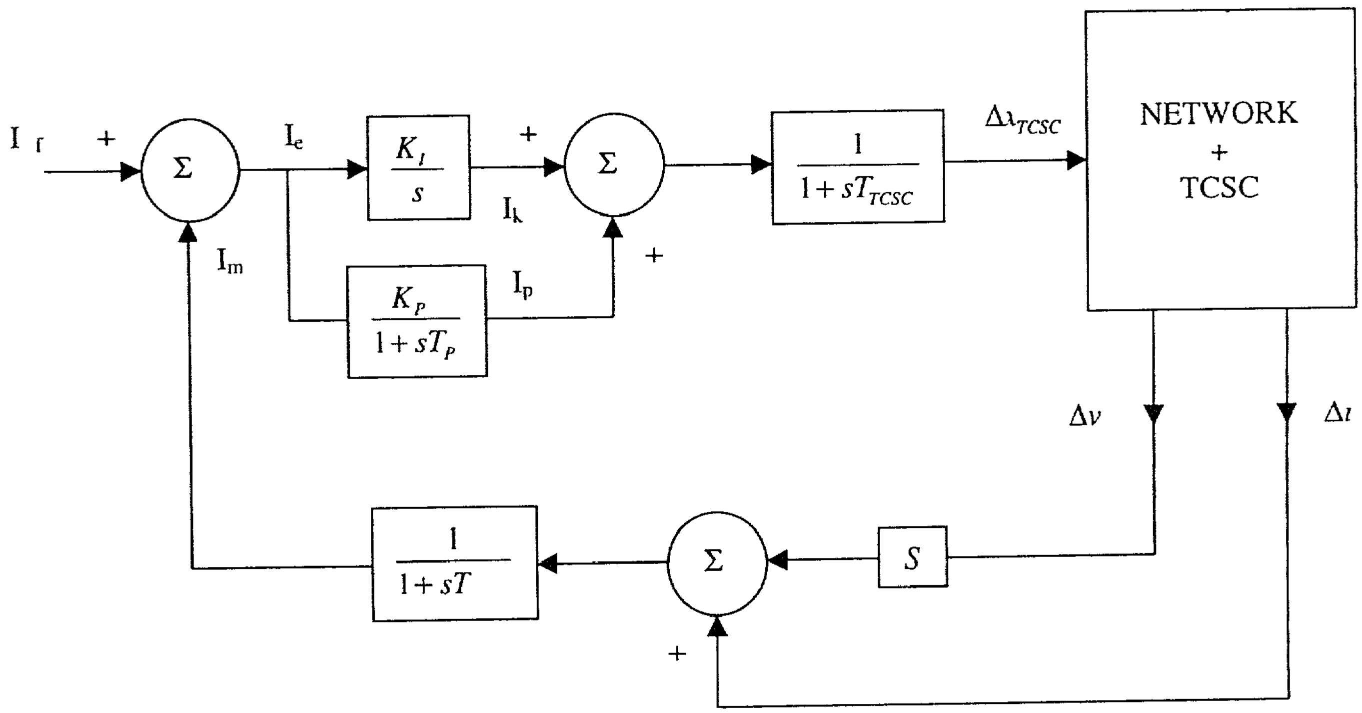


Fig 2 14 Block diagram of CC or CA controller

$$I = -\frac{I}{T} + \frac{1}{T}(\Delta\imath - \frac{\Delta v_t}{X_t}) \tag{2 74}$$

The magnitude of input current to the TCSC is given by

$$\imath = \sqrt{(\imath_D + \imath_Q)} \tag{2 75}$$

Linearizing eqn (2 75)

$$\Delta\imath = \frac{\imath_{D0}}{\imath_0}\Delta\imath_D + \frac{\imath_{Q0}}{\imath_0}\Delta\imath_Q \tag{2 76}$$

The voltage across the TCSC capacitor v_t is also expressed in terms of its D Q axis components as

$$v_t = \sqrt{(v_{tD} + v_{tQ})} \tag{2 77}$$

Linearizing equation (2 77) gives

$$\Delta v_t = \frac{v_{tD0}}{v_{t0}}\Delta v_{tD} + \frac{v_{tQ0}}{v_{t0}}\Delta v_{tQ} \tag{2 78}$$

Eqns (2 76) (2 78) are substituted in eqn (2 74) to give the state equation corresponding to I

The state and output equations of the TCSC with CA controller model can then be written as

$$x_{TCA} = A_{TCA}x_{TCA} + B_{TCA1}u_{TCA1} + B_{TCA2}u_{TCA} \tag{2 79}$$

$$y_{TCA} = C_{TCA}x_{TCA} \tag{2 80}$$

where $x_{TCA} = [\Delta\imath_{tD} \quad \Delta v_{tD} \quad \Delta\imath_{tQ} \quad \Delta v_{tQ} \quad I \quad I_n \quad I_k \quad I_t \quad \Delta x_{TCSC}]$

$y_{TCA} = [\Delta v_{TCD} \quad \Delta v_{TCD}]^t \quad u_{TCA1} = [\Delta\imath_D \quad \Delta\imath_Q] \quad u_{TCA2} = \Delta I_t$

Matrices A_{TCA} B_{TCA1} B_{TCA} C_{TCA} and are defined in Appendix B Sec B 6 1

Constant Current (CC) Controller

The block diagram of this is shown in the fig 2 14 in which S=0

Only eqn (2 73) is changed rest of the eqns are same as CA controller Eqn (2 73) is modified as

$$\dot{I} = -\frac{I_1}{T} + \frac{1}{T}\Delta i \qquad (2\ 81)$$

Eqns (2 76) (2 78) are substituted in eqn (2 81) to give the state equation corresponding to $\dot{I}$

The state and output equations of the TCSC with CC controller model can then be written as

$$\dot{x}_{TCC} = A_{TCC}\, x_{TCC} + B_{TCC1} u_{TCC1} + B_{TCC}\, u_{TCC} \qquad (2\ 82)$$

$$y_{TCC} = C_{TCC}\, x_{TCC} \qquad (2\ 83)$$

where $x_{TCC} = [\Delta i_{tD} \quad \Delta v_{tD} \quad \Delta i_{tQ} \quad \Delta v_{tQ} \quad I \quad I_{t1} \quad I_k \quad I_t \quad \Delta x_{TCSC}]$

$y_{TCC} = [\Delta v_{TCD} \quad \Delta v_{TCD}]^t$ $u_{TCC1} = [\Delta i_D \quad \Delta i_Q]$ $u_{TCC} = \Delta I_r$

Matrices A_{TCC} B_{TCC1} B_{TCC} C_{TCC} and are defined in Appendix B Sec B 6 2

2 9 Derivation of System Model

The interconnection between the various subsystems can be mathematically described by the following relationship

$$u_T = F_T\, y_T \qquad (2\ 84)$$

where

u_T = system input vector =

$[u_{R1}\ u_R\ \ u_{R3}\ \ u_{M1}\ \ u_M\ \ u_{I1}\ \ u_I\ \ u_{N1}\ \ u_N\ \ u_{N3}\ \ u_{N4}\ \ u_{S1}\ \ u_S\ \ u_{TC}]$

y_T = system output vector =

$[y_{R1}\ \ y_R\ \ y_M\ \ y_E\ \ y_{N1}\ \ y_N\ \ y_{N3}\ \ y_{V4}\ \ y_{N5}\ \ y_S\ \ y_{TC}]^t$

Matrix F_T is defined in Appendix B Sec B 7

The state and output equations of all the constituent subsystems are combined to give

$$x_T = A_T x_T + B_T u_T + B\ u_{S3} \tag{2 85}$$

$$y_T = C_T x_T + D_T u_T \tag{2 86}$$

where $x_T = [x_R\ \ x_M\ \ x_I\ \ x_N\ \ x_S\ \ x_{TC}]$

Matrices A_T B_T B C_T and D_T are defined in Appendix B Sec B 7

Substituting eqn (2 86) in eqn (2 84) gives

$$u_T = [I - F_T D_T]^{-1} F_T C_T x_T \tag{2 87}$$

Substituting eqn (2 87) in eqn (2 85) results in

$$x_T = A\ x_T + B\ u_{S3} \tag{2 88}$$

where

$$A = A_T + B_T [I - F_T D_T]^{-1} F_T C_T$$

$$u_{S3} = \Delta V_t$$

interconnections of various subsystems to form the overall system is shown is shown in the fig 2 15

2 10 Modeling of the study systems used in chapters 3,4,5

Modeling of the various subsystems described in this chapter can be used for any combination the study system The only changes to be made are to modify the network model

This chapter describes the modeling of the study system when it comprises all the dynamic devices (PSS SVC with Line Current auxiliary controller TCSC with CA/CC controllers) used (CHAPTER 5) in this thesis To make the PSS and Auxiliary Controllers inactive their gains should be made zero Overall system models for the study systems used in the CHAPTERS 3 4 can be obtained by making the necessary changes in their network matrices based on the guidelines of the modeling described in this chapter

2 11 Conclusions

In this chapter the model for study system comprising the dynamic devices PSS SVC with Line Current auxiliary controller and TCSC with CA/CC controller is developed The model includes the most detailed representation of all subsystems State equations are developed for the purpose of dynamic stability analysis

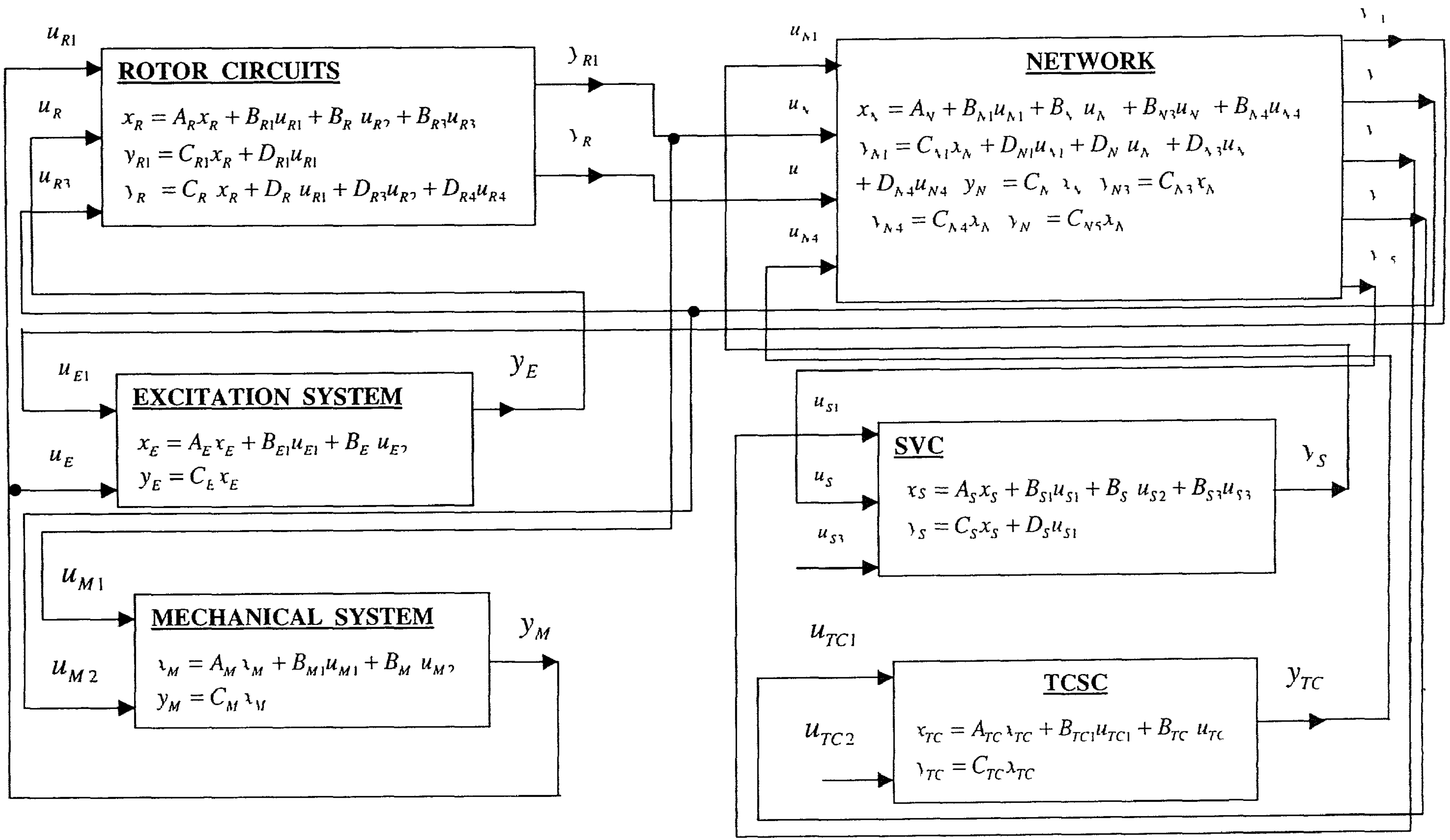


Fig 2 15 INTERCONNECTION OF VARIOUS SUBSYSTEMS IN OVERALL SYSTEM MODEL

Chapter 3

EIGENVALUE ANALYSIS WITH PSS-SVC AND PSS

3 1 Introduction

The system considered is a single machine infinite bus system with two parallel lines In the first type the effects of having Power System Stabilizer (PSS) has been studied and in the second type the influence of both Static Var Compensator (SVC) and PSS on the power transfer has been studied In both the types Thyristor Controlled Series Capacitor (TCSC) is not included in the study system Each line is of 600 Km long having surge impedance load of 540 MW

3 2 Type I Influence of PSS on the system

The study system considered is same as that shown in fig 2 1 excluding the TCSC and SVC The system data has been given in the Appendix C This type is further subdivided in to two cases

1) Study with PSS
2) Study without PSS

Eigenvalue analysis has been done for both the cases for various generating powers Tables 3 1 and table 3 2 shows the eigenvalues for the cases 1 and 2 respectively Table 3 3 shows the steady state power flows and voltage profile of the system Table 3 shows the results of eigenvalue analysis and the parameters of different controllers used Modeling of PSS has been described in chapter 2

TABLE 3 1

System eigenvalues without PSS

P_L = 100 MW	P_g = 500 MW	P_g = 800 MW	P_L = 1000 MW
3 1388±j3679 2	3 1388±j3679 2	3 1388±j3679 2	3 1388±j3679 2
3 146±j3050 88	3 146±j3050 88	3 146±j3050 88	3 146±j3050 88
12 07±j2730 77	12 07±j2730 77	12 07±j2730 77	12 07±j2730 77
13 20±j2102 45	13 20±j2102 45	13 20±j2102 45	13 20±j2102 45
11 857±j1403 2	11 857±j1403 2	11 857±j1403 2	11 857±j1403 2
13 38±j774 88	13 38±j774 88	13 38±j774 88	13 38±j774 88
0 5705±j314 15	0 5705±j314 15	0 5705±j314 15	0 5705±j314 15
25 619±j313 93	25 62±j313 936	25 619±j313 94	25 619±j313 94
26 488±j24 336	26 413±j24 662	26 398±j24 739	26 398±j24 723
33 44	33 8677	34 0104	34 0151
28 2216	28 7345	28 7495	28 6748
0 7061±j4 9647	0 1479±j5 2662	0 2388±j4 5869	0 7556±j3 5716
2 1165	2 8194	1 0486±j0 9966	1 7872±j7761
0 9117±j0 8454	0 7249±j0 883	2 8175	2 4439
16 6667	16 6667	16 6667	16 6667

TABLE 3 2

System eigenvalues with PSS

P_L = 100 MW	P_L = 500 MW	P_g = 800 MW	P_L = 1200 MW
3 1388±j3679 2	3 1388±j3679 2	3 1388±j3679 2	3 1388±j3679 2
3 146±j3050 88	3 146±j3050 88	3 146±j3050 88	3 146±j3050 88
12 07±j2730 77	12 07±j2730 77	12 07±j2730 77	12 07±j2730 77
13 20±j2102 45	13 20±j2102 45	13 20±j2102 45	13 2±j2102 45
11 857±j1403 2	11 857±j1403 2	11 857±j1403 2	11 857±j1403 2
13 38±j774 88	13 38±j774 88	13 38±j774 88	13 38±j774 88
0 5705±j314 15	0 5705±j314 15	0 5705±j314 15	0 5705±j314 15
25 619±j313 94	25 619±j313 94	25 619±j313 94	25 62 ±j313 937
26 895±j24 612	27 463±j25 456	27 5338±j25 59	27 49±j25 4367
34 4906	36 3189	36 5901	36 3639
28 2188	28 7357	28 7839	28 7381
0 9239±j5 8952	0 4991±j7 7357	0 3834±j7 399	0 2471±j3 7501
2 2358	2 8138	2 813	0 9810
0 8072±j0 6786	0 6167±j0 6093	0 7476±j0 69	2 5054±j1 3349
14 4613	11 6328	11 1432	10 0899

TABLE 3

Summary of results (Tables 3 1,3 2)

System under study	Parameters used	Observations
Case 1 Without PSS	For system data refer appendix C	System is stable up to 500 MW
Case 2 With PSS	K_{stab} = 0 244 T_{pss1} = 0 182 T_{pss2} = 0 06	System is stable up to 1200 MW

TABLE 3 3

Steady state conditions of the system

P_g MW	P_1 MW	P_2 MW	V_4 pu	V_3 pu	V_2 pu
1000	519	479	0 971	0 964	0 962
1100	573	525	0 953	0 925	0 942
1200	628	570	0 924	0 861	0 912

Voltages V_4 V_3 V_2 are defined in Fig 2 6

P_1 is the power flow over Line1 (SVC line)

P_2 is the power flow over Line2 (uncompensated line)

From the above tables it is clear that PSS has been proved to be a best choice to mitigate the instability due to electromechanical mode (7 rad/sec) This result is expected as the instability of the system without PSS is mainly due to electromechanical mode (4 5 rad/sec in table 3 1) and PSS is directly acting on it But the steady state power flow over the two lines is not the same

From Table 3 3 with the increase in generating power beyond 1000 MW the midpoint voltage V_3 is decreasing and it attains a value of 0 861 pu at 1200 MW which is highly undesirable This system has no control on the power transfer over the two lines It is seen that under steady state the power sharing between the two lines is improper Hence though the system (with PSS) is able to allow 1200 MW the steady state conditions of the system have led to go for another dynamical device SVC which is described in the following section

3 3 Type II Influence of SVC-PSS on the system

The study system is similar to the system described in fig 2 1 excluding TCSC Line l is compensated at the mid point by a Fixed Capacitor – Thyristor Controlled Reactor (FC TCR) type of Static Var Compensator (SVC) which is provided with a Line Current Auxiliary Controller and its effect on power transfer has been studied with and without PSS

This type is further divided in to 4 sections

1) SVC without Auxiliary Controller
2) SVC with Auxiliary Controller
3) PSS and SVC without Auxiliary Controller
4) SVC with Auxiliary Controller and PSS

The Eigenvalue analysis has been performed for all the four combinations of the system and the eigenvalues have been printed in the tables 3 4 3 5 3 6 and 3 7 Table 4 shows the observations made on the above eigenvalues of all the cases and the parameters used for PSS Modeling of Line current Auxiliary Controller and PSS has been described in the chapter 2

TABLE 3 4

System eigenvalues (SVC without Auxiliary Controller)

P_g = 100 MW	P_g = 500 MW	P_g = 800 MW	P_g = 1000 MW
2 937±j3668 15	2 937±j3668 14	2 937±j3668 12	2 936±j3668 09
2 947±j3039 83	2 947±j3039 82	2 9467±j3039 8	2 946±j3039 77
11 46±j2666 52	11 46±j2666 36	11 46±j2666 08	11 46±j2665 81
12 77±j2038 20	12 77±j2038 04	12 77±j2037 76	12 77±j2037 48
10 94±j1146 52	11 17±j1137 14	11 61±j1120 58	12 091±j1103 3
542 868±j66 89	543 319±j67 91	544 16±j69 686	545 05±j71 472
15 604±j518 47	16 159±j508 98	17 152±j492 27	18 3±j474 7763
25 703±j313 94	25 69±j313 906	25 658±j313 89	25 631±j313 88
0 5765±j314 15	0 5796±j314 14	0 575±j314 132	0 574±j314 126
8 4537±j311 61	8 138±j311 854	7 603±j311 832	6 9571±j311 75
58 8014±j85 63	56 9041±j86 67	54 879±j90 348	53±j94 453
26 3576±j24 48	26 319±j24 709	26 347±j24 796	26 372±j24 804
35 6774	32 7485	34 110±j0 8559	34 15±j0 7386
29 1585	34 6676		
0 5842±j4 8683	0 1974±j5 2787	0 0733±j5 0213	0 2923±j4 5426
0 8508±j0 8044	0 6508±j0 8218	0 7668±j0 9122	0 961±j0 9759
2 231	2 8699	2 9719	2 9680
16 6667	16 6667	16 6667	16 6667
11 1515	11 1515	11 1515	11 1515

TABLE 3 5

System eigenvalues (SVC with Auxiliary Controller)

P_g = 100 MW	P_g = 500 MW	P_g = 800 MW	P_g = 1000 MW
2 937±j3668 15	2 937±j3668 14	2 936±j3668 12	2 936±j3668 09
2 947±j3039 84	2 947±j3039 82	2 9467±j3039 8	2 946±j3039 78
11 46±j2666 53	11 46±j2666 36	11 46±j2666 09	11 46±j2665 81
12 76±j2038 20	12 76±j2038 04	12 76±j2037 76	12 76±j2037 49
10 90±j1146 65	10 18±j1137 28	11 63±j1120 74	12 12±j1203 46
542 402±j69 79	542 78±j72 402	543 63±j74 52	544 532±j76 50
16 2446±j519 0	16 623±j509 78	17 603±j493 22	18 766±j475 89
26 2868±j314 4	26 424±j314 08	26 4173±j314 0	26 409±j313 98
0 566±j314 155	0 594±j314 137	0 618±j314 117	0 6508±j314 13
2 736±j308 906	1 798±j311 264	0 9523±j311 89	0 0013+j312 22
63 771±j87 231	61 476±j71 477	59 335±j77 944	57 475±j80 045
26 392±j24 437	26 364±j24 655	26 437±j24 732	26 468±j24 738
35 181	35 5737	33 8433	37 5646
29 583	33 6836	36 8032	33 4953
0 6029±j4 8681	0 304±j5 3662	0 1141±j5 2535	0 0103±j4 8953
0 8556±j0 8021	0 6448±j0 8239	0 7497±j0 9219	0 9299±j1 0119
2 2309	2 8501	2 91	2 833
3 5329	3 7154	3 7017	3 6484
16 6667	16 6667	16 6667	16 6667

TABLE 3 6

System eigenvalues (PSS and SVC without Auxiliary Controller)

P_g = 100 MW	P_g = 500 MW	P_g = 1000 MW	P_g = 1300 MW
2 937±j3668 15	2 937±j3668 14	2 936±j3668 09	2 935±j3668 05
2 947±j3039 83	2 947±j3039 82	2 946±j3039 78	2 945±j3039 72
11 46±j2666 52	11 46±j2666 36	11 46±j2665 81	11 46±j2665 18
12 771±j2038 2	12 77±j2038 04	12 77±j2037 48	12 77±j2036 86
10 94±j1146 52	11 17±j1137 14	12 091±j1103 3	13 37±j1062 04
542 86±j66 899	543 319±j67 91	545 05 ±j71 472	547 193±j75 53
15 605±j518 47	16 1592±j508 98	18 3±j474 7763	21 63±j432 708
25 703±j313 94	25 69±j313 906	25 632±j313 88	25 57±j313 865
0 5765±j314 16	0 579±j314 141	0 574±j314 126	0 577±j314 103
8 453±j311 619	8 1387±j311 854	6 9571±j311 75	5 208±j311 561
58 801±j85 634	56 907±j86 673	53 006±j94 45	48 19±j104 839
26 645±j24 654	27 292±j25 422	27 523±j25 701	27 561±j25 729
35 6274	35 6932	36 5037	36 728
30 321	34 1732	34 5044	34 1229
14 6732	11 7813	11 0336	10 5347
0 7684±j5 6999	0 5052±j7 6861	0 2841±j7 4879	0 2703±j6 4662
0 7664±j0 6591	0 5771±j0 5484	0 6974±j0 6415	0 9024±j0 6777
2 3361	2 8869	2 9594	2 8708
11 1515	11 1515	11 1515	11 1515

TABLE 3 7

System eigenvalues (SVC with Auxiliary Controller and PSS)

P_g = 100 MW	P_g = 500 MW	P_g = 1000 MW	P_g = 1300 MW
2 937±j3668 15	2 936±j3668 14	2 936±j3668 09	2 935±j3668 04
2 947±j3039 83	2 947±j3039 82	2 945±j3039 77	2 945±j3039 72
11 46±j2666 52	11 46±j2666 36	11 46±j2665 81	11 46±j2665 18
12 77±j2038 20	12 76±j2038 04	12 77±j2037 49	12 77±j2036 86
10 919±j1146 6	11 18±j1137 23	12 114±j1103 4	13 42±j1062 16
542 586±j68 65	542 99±j70 647	544 733±j74 53	546 903±j78 76
15 994±j518 79	16 44±j509 471	18 588±j475 45	21 98±j433 734
26 15±j314 196	26 188±j314 03	26 164±j313 94	26 13±j313 904
0 5206±j314 15	0 584±j314 136	0 5914±j314 09	0 697±j314 107
4 967±j309 89	4 214±j311 438	2 6476±j312 02	0 3131±j312 28
61 772±j86 731	59 787±j81 343	55 954±j86 136	51 384±j94 549
26 719±j24 636	27 473±j25 462	27 759±j25 817	27 806±j25 884
35 4546	35 583±j0 2354	37 482	37 595
30 5664		35 4325	35 0944
15 5982	12 2657	11 326	10 8702
0 8066±j5 7059	0 6167±j7 831	0 3967±j7 9091	0 4056±j7 1566
0 7701±j0 6606	0 5736±j0 5478	0 684±j0 6429	0 8684±j0 6993
2 3381	2 9519	3 0869	2 384
2 7324	2 7222	2 6199	3 1222

TABLE 4

Summary of results (Tables 3 4,3 5,3 6,3 7)

Study system	Parameters used	Observations
1 SVC without Auxiliary Controller	Refer Appendix C	System is stable up to 500 MW
2 SVC with Auxiliary Controller	K_{aux} = 0 013789 T_{aux1} = 0 88699 T_{aux2} = 0 272099	System is stable up to 800 MW
3 PSS and SVC without Auxiliary Controller	K_{stab} = 0 269 T_{pss1} = 0 183 T_{pss2} = 0 06	System is stable up to 1300 MW
4 PSS and SVC with Auxiliary Controller	K_{stab} = 0 269 T_{pss1} = 0 183 T_{pss2} = 0 056 K_{aux} = 0 013789 T_{aux1} = 0 70899 T_{aux2} = 0 359099	System is stable up to 1300 MW

Comparing the results in table 3 and 4 it is observed that having a SVC at the midpoint of Line1 improves the stability of the system. By comparing the results in table 3.4 and 3.5 it is seen that the auxiliary controller improves the damping of electromechanical mode (5 rad/sec) and hence stability of the system. The TCR mode of SVC (311 rad/sec) is moving in to the unstable region for any attempt by auxiliary controller to make the system stable at 1000 MW generation. Therefore the performance of auxiliary controller has been restricted to the parameters given above.

Going through the table 3.7 and comparing them with the results printed in table 3.6 it can be said that the PSS along with SVC Auxiliary Controller improves the damping of the electromechanical mode (7 rad/sec). There are two modes which are making the system unstable one is 312 rad/sec (TCR mode of SVC) and the other one is electromechanical mode (7 rad/sec). Now using Auxiliary Controller damping of the 312 rad/sec mode increases but at the expense of damping of the electromechanical mode. Then by choosing proper parameters for PSS damping of the electromechanical mode increased to a greater extent as the PSS has no influence on the 312 rad/sec mode.

TABLE 3.8

Steady state power flows and voltage profiles

P_L MW	P_1 MW	P_2 MW	V_4 pu	V_3 pu	V_2 pu
1000	526	473	0.979	1.0	0.970
1200	649	549	0.961	1.0	0.950
1300	716	582	0.949	1.0	0.938

Voltages V_4, V_3, V_2 are defined in Fig 2.6

P_1 is the power flow over Line1 (SVC line)

P_2 is the power flow over Line2 (uncompensated line)

Comparing the voltage levels at various buses of table 3.3 and table 3.8 it is observed that having a SVC at the midpoint of Line1 results in to a better voltage profile. Moreover the mid point voltage V_3 is maintained at 1.0 pu. Though the system is stable up to 1300 MW the power sharing between the two lines under steady state is not the same. Going through the table 3.8 as the generating power increases beyond 1000 MW the SVC line is taking more power compared to the other line which is not desirable.

3 4 DISCUSSIONS

In the first type without having any dynamical device the system is unstable beyond 500 MW generation With the addition of PSS the same system is capable of allowing 1200 MW This is expected because the instability to the system is due to the poor damping of electromechanical mode But this system is not recommended because of two reasons

1 Unequal power sharing between the two parallel lines

2 Poor voltage profile at various buses under steady state

Now in the second type effect of SVC and PSS has been studied With only SVC on Line1 the results are again as expected and the system is unable to give way for generation beyond 500 MW When employed with Line Current auxiliary controller the system is able to provide platform for 800 MW generation Now both SVC and PSS have been included in the system leading to the power transfer over two lines up to 1300 MW When both PSS and Auxiliary Controller are employed the system is again attains the power transfer capability of 1300 MW with improved damping of electromechanical mode (7 rad/sec) i e the system(SVC PSS) is more stable

Even after inclusion of SVC though voltage profiles have improved the problem of unequal power sharing between the two parallel lines still persists This can only be improved by having a controllable device on Line2 which in this thesis is TCSC

3 5 CONCLUSIONS

It has been proved that the study system is unstable without any dynamical device (PSS SVC & TCSC) The PSS is proved to be a best choice when instability is mainly due to electromechanical mode Employing SVC in the system not only improves the damping of electromechanical mode but also the steady state voltage profile The combination of SVC with its Auxiliary Controller and PSS have proved to be the best combination for generating powers up to 1300 MW

Chapter 4

EIGENVALUE ANALYSIS WITH TCSC AND PSS

4 1 Introduction

The study system considered is similar to the system depicted in fig 2 1 excluding SVC Line2 is series compensated by a Thyristor Controlled Series Capacitor (TCSC) To obtain equal power sharing between the two parallel lines Line2 has been compensated for 11% of the total reactance of Line2 Each line is of 600 Km long having surge impedance load of 540 MW Eigenvalue studies have been conducted for various generating powers for four different combinations of the study system

1 TCSC with Constant Angle (CA) Controller

2 TCSC with CA Controller and Power System Stabilizer (PSS)

3 TCSC with Constant Current (CC) Controller

4 TCSC with CC Controller and PSS

The operating point of TCSC at 11% compensation has been given in Appendix C The modeling of TCSC and both of its controllers CA and CC have been described in chapter 2 Conclusions are given at the end of the chapter Two sets of parameters have been chosen for CA Controller CA1 is used up to 500 MW and CA2 is used beyond 500 MW

The eigenvalues for all the four cases have been given in tables 4 1 4 2 4 3 and 4 4 in order of their occurrence Table 5 shows the observations made from the above eigenvalues and parameters of controllers used in the system The steady state power flows and the voltages at various buses have been given in table 4 5 Modeling of PSS has been presented in chapter 2

TABLE 4 1

System eigenvalues (TCSC with CA Controller)

P_L = 100 MW—CA1	P_L = 500 MW CA2	P_L =800 MW CA2
9999 9999	9999 9999	9999 9999
3 1382±j3679 3494	3 1382±j3679 3494	3 1382±j3679 3494
3 1460±j3051 0306	3 1460±j3051 0306	3 1460±j3051 0306
12 066±j2731 0156	12 066±j2731 0154	12 066±j2731 0159
13 1969±j2102 6918	13 1968±j2102 6915	13 1968±j2102 6922
11 8529±j1403 3779	11 8529±j1403 3777	11 8529±j1403 3782
13 3791±j774 9816	13 3789±j774 9810	13 3788±j774 9822
0 9548±j433 8743	0 9095±j434 9732	0 8769±j436 7267
24 5046±j313 6685	24 4814±j313 5371	24 3923±j313 3606
0 2671±j309 7940	0 4096±j306 8640	0 5292±j301 7735
0 5094±j199 2786	0 4191±j201 3475	0 4662±j205 0659
26 4859±j24 3477	26 4260±j24 6766	26 4458±j24 7942
34 5820	35 9217	36 3655
32 2890	29 6686	29 1320
20 3976	23 6778	21 0431
0 5451±j7 3023	7813±j11 2676	2 4584±j15 3787
2 9707±j6 3202	0 8936±j7 5675	0 1661±j6 8769
0 9019±j0 8315	0 6983±j0 8725	0 9356±j0 9917
2 1243	2 8401	2 8694
3 0691	5 3972	5 5920
16 6667	16 6667	16 6667

TABLE 4 2

System eigenvalues (TCSC with CA Controller and PSS)

P_g = 100 MW CA1	P_g = 500 MW CA1	P_g = 1000 MW CA2	P_g = 1100 MW CA2
9999 9999	9999 9997	9999 9998	9999 9998
3 13± j3679 34	3 13±j3679 34	3 13± j3679 34	3 13±j 3679 34
3 14± j3051 03	3 14± j3051 03	3 14± j3051 03	3 14±j 3051 03
12 06±j2731 01	12 06±j2731 01	12 06±j2731 01	12 06±j2731 01
13 19±j2102 69	13 19±j2102 69	13 19±j2102 69	13 19±j2102 69
11 85±j1403 37	11 85±j1403 37	11 85±j1403 37	11 85±j1403 37
13 37±j 774 98	13 37± j774 98	13 37±j 774 98	13 37± j774 98
0 95± j433 87	0 904± j440 32	0 83± j438 34	0 85± j439 12
24 50±j 313 66	24 11± j313 14	24 27±j 313 24	24 20±j 313 21
0 26±j 309 79	0 283± j289 13	0 73± j296 48	0 5866±j29 70
0 50± j199 27	1 222± j214 72	0 51± j209 07	0 82± j211 26
26 66±j24 442	27 09± j24 777	27 03±j 25 03	26 04±j 25 01
35 2716	37 9462	37 3706	37 4014
31 8299	8 695±j23 5431	2 48± j20 91	2 50±j 22 61
20 6052	29 5802	29 0501	28 9778
15 7085	0 5687±j8 8615	23 3355	22 9802
0 1853±j7 7073	0 6453±j0 7376	13 1103	13 0339
3 4342±j6 2849	12 4410	0 3879±j7 7818	0 3896±j6 9151
0 8519±j0 7545	10 4234	1 0568±j0 9192	1 3220±j0 932
2 1886	2 8420	2 7864	2 6480
3 0689	3 1137	3 1281	3 1289

TABLE 4 3

System eigenvalues (TCSC with CC Controller)

P_g = 100 MW	P_g = 500 MW	P_g = 800 MW	P_g = 1000 MW
10000 00	10000 00	10000 00	10000 00
3 138±j3679 35	3 138±j3679 35	3 138±j3679 35	3 138±j3679 35
3 146±j3051 03	3 146±j3051 03	3 146±j3051 03	3 146±j3051 03
12 07±j2731 02	12 07±j2731 02	12 07±j2731 02	12 07±j2731 02
13 19±j2102 69	13 19±j2102 69	13 19±j2102 69	13 19±j2102 69
11 85±j1403 38	11 85±j1403 38	11 85±j1403 38	11 85±j1403 38
13 379±j774 98	13 379±j774 98	13 379±j774 98	13 379±j774 98
0 9668±j432 12	0 9668±j432 09	0 9668±j432 06	0 9655±j432 03
24 469±j313 86	24 467±j313 87	24 467±j313 88	24 467±j313 88
0 3645±j314 19	0 3686±j314 32	0 3719±j314 42	0 379±j314 50
0 342±j196 272	0 328±j196 102	0 317±j195 962	0 302±j195 855
26 482±j24 349	26 405±j24 674	26 388±j24 755	26 385±j24 745
33 5703	33 8229	33 8757	33 8392
30 0334	29 7864	29 8552	29 6619
28 7566	29 3660	29 1346	29 1015
0 7414±j5 016	0 289±j5 4229	0 1363±j4 8763	0 2266±j3 8261
2 1162	2 8255	2 8244	0 4796±j2 4281
0 902±j0 832	1 1196±j1 4514	0 9315±j1 8767	2 3120
1 1753±j0 5773	0 7213±j0 8867	1 1254±j0 9644	1 8817±j0 3703
0 1553	0 3842	0 4204	0 4301
16 6667	16 6667	16 6667	16 6667

TABLE 4 4

System eigenvalues (TCSC with CC Controller and PSS)

P_g = 100 MW	P_g = 500 MW	P_g = 1000 MW	P_g = 1200 MW
10000 00	10000 00	10000 00	10000 00
3 138±j3679 35	3 138±j3679 35	3 138±j3679 35	3 138±j3679 35
3 146±j3051 03	3 146±j3051 03	3 146±j3051 03	3 146±j3051 03
12 07±j2731 02	12 07±j2731 02	12 07±j2731 02	12 07±j2731 02
13 20±j2102 69	13 20±j2102 69	13 19±j2102 69	13 19±j2102 69
11 85±j1403 38	11 85±j1403 38	11 85±j1403 38	11 85±j1403 38
13 38±j774 982	13 38±j774 981	13 38±j774 984	13 38±j774 987
0 9668±j432 12	0 9668±j432 09	0 9655±j432 03	0 9643±j432 01
24 469±j313 86	24 467±j313 87	24 467±j313 88	24 467±j313 88
0 3645±j314 19	0 3686±j314 32	0 379±j314 502	0 386±j314 606
0 342±j196 27	0 328±j196 102	0 302±j195 855	0 285±j195 716
26 926±j24 645	27 572±j25 554	27 661±j25 689	27 632±j25 584
34 628	36 5275	36 7499	36 5510
28 7957	29 7716	24 7272	29 7842
30 0935	29 3442	29 0116	28 6744
14 2341	11 2086	10 3411	9 6901
0 9756±j6 048	0 588±j8 1687	0 7277±j7 339	1 275±j5 8[illegible]1
2 2451	2 8184	1 188±j2 088	0 738±j1 9323
0 7954±j0 6576	1 1674±j1 4864	2 6948	2 4385±j0 9571
1 1761±j0 5814	0 6064±j0 5704	0 9261±j0 6231	0 7296
0 1551	0 3826	0 4259	0 3841

TABLE 5

Summary of results (Tables 4 1,4 2,4 3,4 4)

Study system	Parameters	Parameters	Observations
1 TCSC with CA Controller	CA1 $K_{it} = 39\ 694$ $K_{pt} = 10\ 984$ $T_p = 0\ 399$ $T_{tcsc} = 0\ 033$ $T_{pl1} = 0\ 319$ $T_{pl} = 0\ 850$ $T_{meas} = 0\ 0001$	CA2 $K_{itc} = 39\ 984$ $K_{pt} = 9\ 384$ $T_p = 0\ 399$ $T_{tcsc} = 0\ 032$ $T_{pl1} = 0\ 084$ $T_{pl2} = 0\ 970$ $T_{meas} = 0\ 0001$	System is stable up to 800 MW Beyond this 300 rad/sec mode is causing problems
2 TCSC with CA Controller and PSS	CA1 Same as previous case PSS $K_{stab} = 0\ 109$ $T_{pss1} = 0\ 183$ $T_{pss2} = 0\ 060$	CA2 $K_{itc} = 31\ 694$ $K_{ptc} = 10\ 984$ $T_p = 0\ 399$ $T_{tcsc} = 0\ 033$ $T_{pl1} = 0\ 319$ $T_{pl2} = 0\ 850$ $T_{meas} = 0\ 0001$	System is stable up to 1100 MW
3 TCSC with CC Controller	CC $K_{itc} = 0\ 080$ $K_{ptc} = 0\ 1$ $T_p = 0\ 805$ $T_{tcsc} = 0\ 033$ $T_{pl1} = 0\ 133$ $T_{pl2} = 0\ 823$ $T_{meas} = 0\ 0001$		System is stable up to 1000 MW
4 TCSC with CC Controller and PSS	CC Same as the previous case	PSS $K_{stab} = 0\ 269$ $T_{pss1} = 0\ 183$ $T_{pss2} = 0\ 060$	System is stable up to 1200 MW

From table 4 1 it is observed that beyond 800 MW 300 rad/sec (TCR mode of TCSC) mode is making the system unstable

From table 4 2(TCSC CA and PSS) it is observed that though the system is stable at 1200 MW the electromechanical mode is very close to the unstable region Therefore pushing powers on transmission lines beyond 1100 MW is not recommended for this study system

From table 4 4 it is seen that the combination of CC Controller and PSS increases the damping of electromechanical mode (7 rad/sec) by a considerable margin

capability From Table 4 5 it is clear that for the chosen 11% series compensation the power sharing between the two lines is nearly same This system is not recommended for higher generating powers because of its poor voltage profile

4 3 CONCLUSIONS

It has been proved that the study system with CC Controller is better than the CA Controller When combined with PSS again CC Controller results in better damping of electromechanical mode Equal power sharing is obtained with 11 % series compensation

Chapter 5

EIGENVALUE ANALYSIS WITH SVC, TCSC AND PSS

5 1 Introduction

The study system considered for the eigenvalue studies is similar to the system shown in fig 2 1 Line1 is shunt compensated at the mid point by Static Var Compensator (SVC) and Line2 is series compensated by a Thyristor Controlled Series Capacitor (TCSC) Each line is of 600 Km long having surge impedance load of 540 MW The chosen series compensation for TCSC is 11% of total reactance of Line2 The modeling of SVC TCSC and their controllers and Power System stabilizer (PSS) has been described in chapter2 Eigenvalue studies have been conducted for various combinations of the study system They are as follows

1) SVC and TCSC with Constant Angle (CA) Controller
2) SVC PSS and TCSC with CA Controller
3) SVC with Line Current Auxiliary Controller and TCSC with CA Controller
4) SVC and TCSC with Constant Current (CC) Controller
5) SVC PSS and TCSC with CC Controller
6) SVC with Line Current Auxiliary Controller and TCSC with CC Controller

The performance of above 6 cases have been studied and discussed Conclusions are given at the end of the chapter Here SVC implies SVC with its voltage regulator

Like in the chapter 4 here also two sets of parameters have been used for CA Controller Eigenvalues for all the six cases listed above have been given in the Tables 5 1 5 2 5 3 5 4 5 5 and 5 6 in the order of their occurrence in the list above CA1 is chosen for powers up to 500 MW and CA2 is used for powers beyond 500 MW The parameters of all the controllers and the observations made on the above eigenvalues of all the cases as been given in Table 6 Steady state conditions of the system are given in the Table 5 7

TABLE 5 1

System eigenvalues (SVC and TCSC with CA Controller)

P_g = 100 MW CA1	P_g = 500 MW CA1	P_g =800 MW CA2	P_g = 1000 MW CA2
9999 9999	9999 9997	9999 9999	9999 9998
2 937±j3668 31	2 937±j3668 29	2 937±j3668 28	2 936±j3668 26
2 947±j3039 99	2 947±j3039 98	2 946±j3039 96	2 946±j3039 94
11 46±j2666 77	11 46±j2666 63	11 46±j2666 37	11 46±j2666 12
12 77±j2038 45	12 77±j2038 30	12 77±j2038 05	12 77±j2037 79
10 94±j1146 64	11 16±j1137 96	11 55±j1122 75	11 98±j1106 95
542 87±j66 89	543 28±j67 83	544 06±j69 47	544 87±j71 108
15 59±j518 58	16 103±j509 82	17 01±j494 46	18 037±j478 47
0 953±j433 93	0 942±j440 08	0 9238±j436 24	0 9044±j437 24
24 62±j313 69	24 254±j313 13	24 48±j313 36	24 384±j313 25
0 25±j309 843	8 127±j311 884	7 66±j311 88	7 098±j311 811
8 434±j311 61	0 047±j290 312	0 319±j303 30	0 394±j300 158
0 544±j199 22	1 467±j213 72	0 672±j203 889	0 691±j206 247
58 83±j85 57	57 018±j86 49	55 148±j89 83	53 442±j93 561
26 36±j24 499	26 375±j24 76	26 396±j24 837	26 453±j24 88
35 7842	36 5933	35 357±j0 4766	35 493±j0 6391
34 3149	34 8456		
21 5440	7 9224±j22 7	22 2718	2 266±j16 8477
0 2496±j7 188	0 4965±j7 1136	1 5471±j14 465	20 6945
2 9533±j6 3114	10 7122	0 3190±j7 1676	0 003±j6 5357
0 8440±j0 8006	0 6398±j0 8159	0 7403±j0 9042	0 9019±j0 9739
2 2397	2 8798	2 9843	2 9869
3 0695	3 1195	6 0892	6 1983

TABLE 5 21

System eigenvalues (SVC , PSS(PSS1) and TCSC with CA Controller)

P_g = 100 MW CA1	P_g = 500 MW CA1	P_g = 1000 MW CA2	P_g =1200 MW CA2
9999 9999	9999 9997	9999 9998	9999 9998
2 937±j3668 31	2 936±j3669 29	2 936±j3668 26	2 94±j3668 229
2 946±j3039 99	2 95±j3039 981	2 946±j3039 94	2 95±j3039 91
11 46±j2666 77	11 46±j2666 63	11 46±j2666 12	11 46±j2665 77
12 77±j2038 45	12 77±j2038 30	12 767±j2037 8	12 77±j2037 45
10 94±j1146 63	11 16±j1137 96	11 98±j1106 95	12 64±j1084 61
542 86±j66 89	543 28±j67 83	544 87±j71 108	546 02±j73 353
15 592±j518 58	16 103±j509 82	18 04±j478 472	19 677±j455 79
0 953±j433 927	0 942±j440 078	0 904±j437 24	0 891±j438 244
24 617±j313 69	24 254±j313 13	24 38±j313 254	24 26±j313 163
0 2498±j309 84	8 127±j311 884	7 0978±j311 81	6 216±j311 699
8 434±j311 606	0 047±j290 312	0 394±j300 158	0 489±j296 702
0 544±j199 213	1 467±j213 72	0 691±j206 247	0 699±j208 304
58 825±j85 573	57 019±j86 491	53 444±j93 559	50 981±j99 034
26 477±j24 514	26 899±j24 619	26 996±j24 959	27 042±j24 986
35 6934	37 9246	37 5622	37 6525
34 7310	34 8404	34 8787	34 9126
24 6778	10 7972	21 245±j1 8831	20 523±j0 96
21 2399	21 3986		
0 0102±j7 4408	8 4432±j22 502	2 357±j16 1863	2 939±j18 789
3 2297±j6 3205	0 5706±j8 3554	0 3540±j8 1322	0 0960±j7 0964
0 8113±j0 7390	0 6089±j0 6956	0 7898±j0 8283	0 9825±j0 8840
2 2941	2 8932	2 9827	2 9428
3 0694	3 1194	6 2037	6 2867

TABLE 5 22

System eigenvalues (SVC , PSS(PSS2) and TCSC with CA Controller)

P_g = 100 MW CA1	P_g = 500 MW CA1	P_g = 1000 MW CA2	P_g = 1400 MW CA2
9999 9999	9999 9997	9999 9998	9999 9998
2 937±j3668 31	2 936±j3668 29	2 936±j3668 26	2 936±j3668 19
2 947±j3039 99	2 947±j3039 98	2 946±j3039 94	2 945±j3039 87
11 46±j2666 77	11 46±j2666 63	11 46±j2666 12	11 46±j2665 28
12 77±j2038 45	12 77±j2038 30	12 77±j2037 79	12 77±j2036 95
10 94±j1146 64	11 16±j1137 96	11 98±j1106 95	13 74±j1051 4
542 87±j66 894	543 28±j67 83	544 87±j71 108	547 76±j76 55
15 592±j518 58	16 102±j509 82	18 037±j478 47	0 949±j439 345
0 953±j433 927	0 942±j440 078	0 904±j437 24	22 604±j421 68
24 617±j313 69	24 254±j313 13	24 384±j313 25	24 09±j313 078
0 2498±j309 84	8 127±j311 884	7 098±j311 812	4 77±j311 568
8 434±j311 61	0 047±j290 312	0 394±j300 158	0 356±j292 65
0 544±j199 213	1 467±j213 72	0 691±j206 247	1 009±j212 089
58 829±j85 575	57 024±j86 489	53 444±j93 553	46 878±j107 66
99 9976	99 9706	99 9590	99 9560
26 422±j24 326	26 299±j23 846	26 769±j24 013	26 921±j24 156
35 8321	34 879±j0 1288	34 559±j1 2057	34 832±j1 7437
34 0327			
21 4777	8 2703±j21 923	21 0385	2 9315±j21 476
0 0689±j7 5316	1 0581±j8 4351	1 8370±j16 044	17 8739
3 2271±j6 2321	10 8010	1 0125±j8 1127	0 0822±j5 5216
0 8101±j0 7427	0 6055±j0 6999	0 7870±j0 8075	1 47±j0 8632
2 2871	2 8910	2 9834	2 7386
3 0694	3 1194	6 1996	6 3507

TABLE 5 3

System eigenvalues

(SVC with Line Current aux Contr and TCSC with CA Controller)

P_g = 100 MW CA1	P_g = 500 MW CA2	P_g = 800 MW CA2	P_g = 1000 MW CA2
9999 9999	9999 9999	9999 9999	9999 9998
2 937±j3668 31	2 936±j3668 30	2 936±j3668 28	2 936±j3668 26
2 947±j3039 99	2 95±j3039 98	2 946±j3039 96	2 946±j3039 94
11 459±j2666 8	11 459±j2666 6	11 46±j2666 37	11 46±j2666 12
12 77±j2038 45	12 76±j2038 30	12 76±j2038 05	12 77±j2307 79
10 93±j1146 68	11 16±j1138 06	11 56±j1122 85	12 01±j1107 05
542 72±j67 789	542 93±j70 721	543 71±j72 583	544 53±j74 344
15 802±j518 74	16 41±j510 32	17 299±j495 06	18 34±j479 17
0 945±j433 919	0 898±j434 752	0 903±j436 234	0 883±j437 234
24 91±j313 872	25 19±j313 704	25 117±j313 50	25 05±j313 38
0 256±j309 839	4 01±j311 474	3 385±j311 89	2 654±j312 06
6 588±j310 65	0 388±j307 526	0 271±j303 247	0 324±j300 113
0 489±j189 20	0 336±j200 806	0 574±j203 905	0 596±j206 264
60 44±j86 321	60 04±j80 735	58 083±j82 115	56 397±j84 679
26 371±j24 481	26 384±j24 695	26 472±j24 813	26 537±j24 86
35 6288	35 514±j0 4578	36 03±j0 7347	36 299±j0 856
34 3193			
21 6585	24 7174	22 3405	20 6870
11 0435	6 9851	7 0162	6 2540
0 2484±j7 1781	0 1561±j10 982	1 6294±j14 491	2 332±j16 899
2 9580±j6 3106	1 0453±j7 4731	0 3057±j7 1650	0 0173±j6 5648
0 8474±j0 8022	0 6735±j0 8149	0 7323±j0 9019	0 8850±j0 9722
2 2395	5 8651	6 1308	7 0089
3 0695	2 8799	2 9847	2 9878

TABLE 5 4

System eigenvalues (SVC and TCSC with CC Controller)

P_g = 100 MW	P_g = 500 MW	P_g = 800 MW	P_g =1000 MW
10000 00	10000 00	10000 00	10000 00
2 937±j3668 31	2 936±j3668 30	2 936±j3668 28	2 936±j3668 26
2 947±j3039 99	2 947±j3039 98	2 95±j3039 96	2 946±j3039 94
11 46±j2666 77	11 46±j2666 63	11 46±j2666 37	11 46±j2666 12
12 77±j2038 45	12 77±j2038 30	12 77±j2038 05	12 77±j2037 79
10 94±j1146 63	11 16±j1137 96	11 55±j1122 75	11 98±j1106 95
542 87±j66 89	543 28±j67 83	544 06±j69 467	544 87±j71 08
15 59±j518 58	16 10±j509 81	17 01±j494 456	18 03±j478 468
0 958±j432 167	0 963±j432 025	0 963±j431 907	0 969±j431 82
24 58±j313 879	24 56±j313 847	24 52±j313 844	24 48±j313 85
0 371±j314 278	0 391±j314 73	0 412±j315 081	0 4187±j315 33
8 434±j311 678	8 15±j31 87	7 681±j311 863	7 107±j311 789
0 344±j196 119	0 269± j195 51	0 1986±j195 06	0 161±j194 753
58 825±j85 57	57 03±j86 461	55 158±j89 810	53 455±j93 533
26 355±j24 5	26 313±j24 721	26 332±j24 809	26 35±j24 819
35 7801	34 7936	33 957±j0 7418	33 95±j0 418
29 743±j1 072	32 0099		
	29 7637	28 4268	27 7723
0 6801±j4 9558	0 8479±j5 5761	0 7779±j3 6933	0 1641±j3 5221
1 2193±j1 2675	1 2871±j2 9438	1 6398±j5 5062	2 4358±j5 8471
2 2275	2 8702	2 9755	2 9738
0 8437±j0 8007	0 6450±j0 8716	0 7628±j0 9068	0 9660±j0 9633
0 1727	0 2465	0 2555	0 2585

TABLE 5 5

System eigenvalues (SVC , PSS and TCSC with CC Controller)

P_g =100 MW	P_g = 500 MW	P_g = 1000 MW	P_g =1100 MW
10000 00	10000 00	10000 00	10000 00
2 937±j3668 31	2 936±j3668 29	2 936±j3668 26	2 936±j3668 25
2 947±j3039 99	2 947±j3039 98	2 946±j3039 94	2 96±j3039 93
11 46±j2666 77	11 46±j2666 63	11 46±j2666 12	11 46±j2665 96
12 77±j2038 45	12 77±j2038 30	12 77±j2037 79	12 77±j2037 63
10 94±j1146 64	11 16±j1137 96	11 98±j1106 95	12 28±j1096 78
542 87±j66 89	543 28±j67 83	544 87±j71 11	545 39±j72 14
15 59±j518 58	16 10±j509 81	18 04±j478 47	18 75±j468 16
0 958±j432 167	0 963±j432 03	0 969±j431 817	0 969±j431 77
24 58± j313 88	24 56±j313 85	24 48±j313 85	24 46±j313 86
0 37±j314 278	0 391±j314 73	0 419±j315 33	0 437±j315 45
8 434±j311 618	8 15±j311 874	7 107±j311 789	6 71±j311 74
0 344±j196 119	0 269±j195 508	0 161±j194 75	0 122±j194 60
58 83±j85 566	57 034±j86 461	53 46±j93 532	52 35±j95 988
101 0999	101 0071	101 0058	101 0057
26 39±j24 504	26 44±j24 7475	26 509±j24 853	26 52±j24 8476
35 7780	34 7951	33 999±j0 475	33 3661
	32 1252		34 4860
29 763±j1 0745	29 7295	27 7637	27 4791
0 626±j5 2134	0 5887±j6 2457	1 9649±j6 0392	2 4393±j6 1667
1 2278±j1 2724	1 4071±j2 9677	0 6022±j4 2381	0 2616±j4 1110
0 8071±j0 7261	0 6112±j0 6748	0 8001±j0 7791	0 8843±j0 7929
2 902	2 8806	2 9655	2 9510
0 1726	0 2464	0 2584	0 2595

TABLE 5 6

System eigenvalues

(SVC with Line Current aux Contr and TCSC with CC Controller)

P_g = 100 MW	P_g = 500 MW	P_g = 1000 MW	P_g = 1100 MW
10000 00	10000 00	10000 00	10000 00
2 937±j3668 31	2 936±j3668 30	2 936±j3668 26	2 936±j3668 25
2 947±j3039 99	2 947±j3039 98	2 946±j3039 94	2 95±j3039 93
11 46±j2666 77	11 46±j2666 63	11 46±j2666 12	11 46±j2665 96
12 77±j2038 45	12 77±j2038 30	12 77±j2037 79	12 77±j2037 63
10 92±j1146 70	11 16±j1138 04	12 00±j1107 03	12 30±j1096 87
542 63±j68 34	543 0±j17 165	544 59±j73 72	545 12±j74 80
15 93±j518 846	16 35±j510 224	18 28±j479 03	19 0±j468 779
0 946±j432 15	0 978±j432 019	0 953±j431 81	0 954±j431 77
25 03±j314 14	25 06±j313 97	25 02±j313 91	25 0±j313 895
0 368±j314 278	0 391±j314 729	0 4197±j315 32	0 439±j315 449
5 473±j310 08	4 796±j311 503	3 452±j311 98	2 959±j312 05
0 245±j196 099	0 168±j195 526	0 059±j194 79	0 019±j194 64
61 41±j86 813	59 557±j81 963	56 021±j86 528	54 958±j88 486
26 374±j24 472	26 343±j24 696	26 389±j24 791	26 396±j24 784
35 5166	35 1489	35 9786	36 2309
29 837±j1 075	32 6910	33 0475	32 6776
	29 5352	27 8049	27 5525
0 6881±j4 9572	0 8482±j5 6245	2 3672±j5 7971	2 7243±j5 9582
1 2214±j1 2691	1 3398±j2 9606	0 3696±j3 7908	0 1088±j3 6272
0 8475±j0 8020	0 6366±j0 8157	0 9167±j0 9741	1 0595±j0 9963
2 2275	2 8689	2 9654	2 9400
4 3867	4 1614	4 4172	4 3914
0 1728	0 2469	0 2590	0 2601

TABLE 6

Summary of results (Tables 5 1,5 21,5 22,5 3,5 4,5 5 5 6)

Study system	Parameters	Parameters	Observations
1 SVC and TCSC with CA Controller	CA1 K_{itc} = 38 984 K_{ptc} = 10 984 T_p = 0 399 T_i = 0 032 T_{pl1} = 0 319 T_{pl} = 0 890 T_{meas} = 0 0001	CA2 K_{itc} = 39 884 K_{pt} = 10 184 T_p = 0 399 T_i = 0 032 T_{pl1} = 0 084 T_{pl2} = 0 970 T_m = 0 0001	System is stable up to 1000 MW
2 SVC PSS and TCSC with CA Controller	CA1 Same as the previous case PSS1 K_{stab} = 0 1 T_{pss1} = 0 129 T_{pss} = 0 04	CA2 Same as the previous case PSS2 K_{stab} =0 1 T_{pss1} = 0 152 T_p = 0 010	PSS1 System is stable up to 1100 MW PSS2 System is stable up to 1400 MW
3 SVC with Auxiliary Controller and TCSC with CA Controller	CA1 Same as the previous case + Aux Controller1 K_{aux}=0 00839 T_{aux1}=0 15299 T_{aux2}=0 08967	CA2 Same as the previous case + Aux Controller2 K_{aux}=0 013308 T_{aux1}=0 31299 T_{aux} =0 14467	System is stable up to 1000 MW
4 SVC and TCSC with its CC Controller	CC K_{itc} = 0 156 K_{pt} = 0 450 T_p = 0 805 T_i = 0 033 T_{pl1} = 0 133 T_{pl} = 0 823 T_{meas} = 0 0001		System is stable up to 1000 MW
5 SVC PSS and TCSC with CC Controller	CC Same as in the previous case	PSS K_{stab} = 0 105 T_{pss1} = 0 024 T_{pss2} = 0 0099	System is stable up to 1100 MW
6 SVC with Auxiliary Controller and TCSC with CC Controller	CC Same as in the previous case	Aux Controller K_{aux} = 0 01331 T_{aux1} = 0 3929 T_{aux2}=0 22467	System is stable up to 1100 MW

From Table 5 1(SVC and TCSC with CA Controller) though the system is stable up to 1000 MW the operation at 1000 MW is not feasible because of the poor damping of electromechanical mode (6 5 rad/sec) Any attempt to make this mode stable at 1000 MW is causing another mode (11 rad/sec) to become unstable at 500 MW

From the Table 5 21(SVC PSS and TCSC with its CA Controller) the system is capable of transferring powers up to 1100 MW but it is unstable at 500 MW for CA2 and is stable for CA1 at the same power The instability is mainly due to 267 rad/sec mode Parameters used for PSS are PSS1 in the table 6

Table 5 22 shows the eigenvalues obtained for PSS2 (Table 6) It is observed that PSS improves the power transfer capability of the system up to 1400 MW In this case also system is unstable at 500 MW with CA2 It is observed that by increasing the leading compensation offered by PSS the stability of the system can be improved for higher generating powers But realization of this parameters is difficult in practice In this case also instability to the system at 500 MW is caused by 267 rad/sec mode

In case 3 (Table 5 3) Aux Controller1 and Aux Controller2 are used along with CA1 and CA2 respectively It is observed that the use of Line Current Auxiliary Controller improves the damping of electromechanical mode (7rad/sec) and hence the power transfers capability of the system

From Table 5 6 (SVC PSS and TCSC with CC Controller) it is observed that the damping of electromechanical mode (6 rad/sec) increased by a considerable margin

TABLE 5 7

steady state conditions of the system

P_g MW	P_1 MW	P_2 MW	V_4 pu	V_3 pu	V_5 pu	V_6 pu	V_7 pu
800	388	411	0 992	1 0	0 985	0 961	0 962
1000	495	504	0 980	1 0	0 971	0 931	0 932
1100	551	547	0 972	1 0	0 963	0 911	0 913
1200	611	588	0 963	1 0	0 952	0 889	0 890

Voltages V_4 V_5 V V_6 V_7 are defined in Fig 2 6

P_1 is the power flow over Line1 (SVC line)

P_2 is the power flow over Line2 (TCSC line)

From the above Table 5 7 with increase in generating power (up to 1000MW) the TCSC line is carrying slightly more power compared to the SVC line But beyond 1000 MW SVC line starts carrying more power compared to TCSC line The steady state voltage profile is good up to 1100 MW Even for 1200 MW V_4 V_5 are good but the voltage on either side of TCSC have reduced by considerable margin These voltages V_6 & V_7 can be improved if shunt capacitors are placed at those points But under no load or lightly loaded conditions these voltages may raise to intolerable levels The recommendations may be to use switched shunt capacitors at these two nodes (V_6 & V_7) Use of switched capacitors is beyond the scope of this thesis For the Chosen 11% series compensation for the TCSC the steady state power flows over the two parallel lines is almost same at 1200 MW

5 2 DISCUSSIONS

Comparing the Tables 5 1 5 21 and 5 22 it is observed that power transfer capability of the system increased with the use of PSS in the system Comparing tables 5 1 & 5 3 it can be seen that the Line Current Auxiliary Controller increases the system stability The combination of CA and Auxiliary Controller increases the damping of electromechanical mode (6 56 rad/sec) to 10 times at 1000 MW power level From Table 5 21 and 5 22 it is clear that the system is unstable for the combination of CA2 and PSS at 500 MW In this case it is recommended that not to go for PSS when generating powers are below 800 MW and to use PSS for powers beyond 800 MW Thus by properly scheduling the CA and PSS controllers the system can reach powers up to 1400 MW Only one set of parameters has been used for CC controller By comparing CA and CC (Table 5 1 & 5 4) Controllers it is observed that the TCSC with CC Controller gives better results compared to TCSC and CA Controller Looking at the results in table 5 4 (TCSC with CC Controller) table 5 5 (CC Controller and PSS) the combination of CC Controller and PSS has made the system stable up to 1100 MW This result is expected as PSS is doing its job nicely by improving the damping of electromechanical mode Comparing CC Controller and the combination of CC Controller and Line Current Auxiliary Controller it is observed that the latter is

better than the former in terms of power transfer on the two lines Looking at the results of all the cases it is observed that TCSC with CC Controller is better than TCSC with CA Controller The steady state power flow over the two lines is almost same up to the power level of 1200 MW and also voltage profile at various buses is good

5 3 Justification for having both TCSC and SVC in the system

In chapter 3 it is observed that the combination of SVC with Line Current Auxiliary Controller and PSS has made the system stable up to 1300 MW From chapter 4 it can be seen that combination of TCSC with CC controller and PSS increases the power transfer capability of the system up to 1200 MW In both the cases it is clear that the system is stable up to 1200 MW with one or the other device Then the question may arise Why this work recommends the system with both SVC TCSC and PSS The answer is as follows

The studies have been done for small series compensations like 11% For higher series compensations SSR problem will occur and both SVC with its Auxiliary Controllers and TCSC can be used for damping SSR Also to improve the steady state voltage profiles at higher generating powers enough reactive power support is needed on the long transmission lines This can be achieved by employing a SVC at the mid point of the line1 SVC is a dynamic device which can be used to supply both lagging and leading reactive power requirements

Without having a controllable device on Line2 it is not possible to obtain control on power flow over two parallel lines Among the two devices SVC & TCSC control of power is possible with TCSC and also TCSC is not merely used for the purpose of power boosting It has numerous advantages During fault conditions TCSC can be made to operate under bypass mode to reduce the magnitude of fault current flowing in the line Thus the transient stability can be improved using both TCSC and SVC From the above discussions with proper coordination between TCSC on line2 and SVC on line1 the system can be made more stable under steady state and transient conditions

5 4 CONCLUSIONS

It is observed that TCSC with CC Controller is better than TCSC with CA Controller In all the cases when PSS added to the system stability improves thereby improving the power transfer capability of the system Both CA and CC Controllers when combined with Line Current Auxiliary Controller results in to a more stable systems It is observed that by properly scheduling the CA Controllers at different power levels the system stability can be improved For the chosen parameters of CC CA SVC and PSS there is no adverse interaction between the two FACTS devices (SVC and TCSC) For the same power level CC controller gives more stable system in terms damping of the system eigenvalues compared to CA controller

Chapter 6

CONCLUSIONS

In this thesis a Single Machine Infinite Bus System (SMIB) has been studied with two parallel lines One of the lines has a Static Var Compensator (SVC) connected at the midpoint whereas the other has a Thyristor Controlled Series Capacitor (TCSC) The two lines are 600 Km long having natural load of 540 MW The generator is equipped with a PSS Eigenvalue analysis is performed to evaluate system stability Controller parameters are determined which ensure a satisfactory coordinated control of the two FACTS devices (SVC and TCSC) together with PSS Different configurations of study system are investigated The following observations are made

The system is stable up to 500 MW when no dynamical device is present in the system Study system considered does not include TCSC SVC and PSS When provided with Power System Stabilizer(PSS) system remains stable up to 1200 MW but at the expense of steady state voltage profile

When the study system has SVC on Line 1 and Line 2 is uncompensated with the presenceof PSS the power transfer over the two lines reaches 1300 MW It is shown that Line Current Auxiliary Controller of SVC increases damping of the system and SVC improves the voltage profile

The next study system has TCSC on Line 2 and Line 1 is uncompensated Two types of controller namely (1) Constant Angle (CA) and (2) Constant Current (CC) have been employed with TCSC It is shown that TCSC with CC controller contributes more damping to the system compared to TCSC with CA controller Again when PSS is included in the system power transfer capability of the system increases to 1200 MW

In the final study both SVC and TCSC are included in the system The chosen operating point of 11% series compensation for TCSC results in equal power flow on the two lines under steady state and the presence of SVC at the midpoint of Line 1 improves the steady state voltage profile of the system

It is observed that generally better stability characteristic is obtained with CC control than CA control However with two separate sets of CA controller parameters

one for low power range and the other for high power range stable system operation has been obtained up to about 1400 MW of total power transfer With CC control and with only one set of parameters for the whole power range stable operation has been obtained up to about 1100 MW These results are in the nature of preliminary results and better results in terms of maximum stable power transfer on the lines can be obtained with better designs of the various controllers

SCOPE FOR FUTURE WORK

- The study system can be simulated on EMTDC/PSCAD package for studying the transient behavior of the system
- The studies can be extended to multi area systems with double circuit tie lines
- Studies can be extended to realistic systems such as the Northern Regional Electricity Board (NREB)

APPENDIX A

SYNCHRONOUS MACHINE MODEL PARAMETERS

In this Appendix expressions are given for the various constants which are used in the synchronous machine model [2]

The constants $a_1 - a_8$ are defined as

$$\begin{bmatrix} a_1 & a \\ a_3 & a_4 \end{bmatrix} = -\frac{w}{x_f x_l - x'^2_{fl}} \begin{bmatrix} R_f x_l & -R_f x_{fl} \\ -R_l x_{fl} & R_l x_f \end{bmatrix}$$

$$\begin{bmatrix} a_5 & a_6 \\ a_7 & a_8 \end{bmatrix} = -\frac{w}{x_g x_k - x_{gk}} \begin{bmatrix} R_g x_k & -R_g x_{gk} \\ -R_k x_{gk} & R_k x_g \end{bmatrix}$$

The constants $b_1 - b_6$ are defined as

$$b_1 = \frac{w R_f}{x_{ll}} \qquad \begin{bmatrix} b \\ b_3 \end{bmatrix} = \frac{w}{x_f x_l - x_{fl}} \begin{bmatrix} R_f(x_{ll} x_l - x_{ll} x_{fl}) \\ R_l(x_f x_{ll} - x_{fl} x_{ll}) \end{bmatrix}$$

$$\begin{bmatrix} b_5 \\ b_6 \end{bmatrix} = \frac{w}{x_g x_k - x_{gk}} \begin{bmatrix} R_g(x_{lg} x_k - x_{lk} x_{gk}) \\ R_k(x_g x_{lk} - x_{gk} x_{lg}) \end{bmatrix}$$

The constants $c_1 - c_4$ are given as

$$c_1 = \frac{x_{ll} x_h - x_{lh} x_{fl}}{x''_l \,(x_f x_l - x_{fl})} \qquad c = \frac{x_{ll} x_l - x_{fh} x_{ll}}{x''_l \,(x_f x_l - x_{fl})}$$

$$c_3 = \frac{x_{fs}x_k - x_{fk}x_{sk}}{x_d''(x_s x_k - x_{sk}^2)} \qquad c_4 = \frac{x_{qk}x_s - x_{sk}x_f}{x_q''(x_s x_k - x_{sk}^2)}$$

where

$x_f \quad x_h \quad x_s \quad x_k$ are reactances of the rotor coils specified by the subscripts

$R_f \quad R_h \quad R_s \quad R_k$ are resistances of the rotor coils specified by the subscripts

$x_{df} \quad x_{dh} \quad x_{fh} \quad x_{sk} \quad x_{qs} \quad x_{qk}$ are mutual reactances between rotor coils specified by the subscripts

The resistances and reactances of the various rotor coils are defined as follows

$$x_{df} = x_{dh} = x_{fh} = x_d - x_l \qquad x_{qs} = x_{qk} = x_{sk} = x_q - x_l$$

$$x_{hl} = \frac{(x_d' - x_l)(x_d'' - x_l)}{(x_d' - x_d'')} \qquad x_{fl} = \frac{(x_d' - x_l)x_{df}}{(x_d - x_d')}$$

$$x_{sl} = \frac{(x_q' - x_l)(x_q'' - x_l)}{(x_q' - x_q'')} \qquad x_{kl} = \frac{(x_q' - x_l)x_{qk}}{(x_q - x_q')}$$

$$x_f = x_{df} + x_{fl} \qquad x_h = x_{df} + x_{hl}$$

$$x_s = x_{qs} + x_{sl} \qquad x_k = x_{qk} + x_{kl}$$

$$R_f = \frac{x_{df}^2}{w_s T_d' (x_d - x_d')} \qquad R_h = \frac{(x_d' - x_l)}{w_s T_d'' (x_d' - x_d'')}$$

$$R_s = \frac{(x_q - x_l)}{w_s T_{qo} (x_q - x_q')} \qquad R_k = \frac{x_{qk}}{w_s T_q'' (x_q - x_q')}$$

where

x_l is the stator leakage reactance

$x_d \quad x_d' \quad x_d''$ are the direct axis synchronous, transient and subtransient reactances respectively

$x_q \quad x_q' \quad x_q''$ are the quadrature axis synchronous, transient and subtransient reactances respectively

T_l I_l are the direct axis transient and subtransient open circuit time constants respectively

T_l T_q are the quadrature axis transient and subtransient open circuit time constants respectively

APPENDIX B

DETAILS OF SYSTEM MODEL DESCRIBED IN CHAPTER 2

B 1 Rotor Circuits

Substituting eqn (2 7) in eqn (2 6)

$$\begin{aligned}
\dot{\Psi}_f &= a_1\Psi_f + a\ \Psi_l + b_1 v_f + b\ \cos\delta\ i_D - b\ \sin\delta\ i_Q \\
\dot{\Psi}_l &= a_3\Psi_f + a_4\Psi_l + b_3\ \cos\delta\ \ i_D - b_3 \sin\delta\, i_Q \\
\dot{\Psi}_s &= a_5\Psi_s + a_6\Psi_k + b_5 \sin\delta\, i_D + b_5 \cos\delta\, i_Q \\
\dot{\Psi}_k &= a_7\Psi_s + a_8\Psi_k + b_6 \sin\delta\, i_D + b_6 \cos\delta\, i_Q
\end{aligned} \quad \text{(B 1)}$$

The state equation for the rotor circuits is obtained by linearizing eqn (B 1)

$$\dot{x}_R = A_R x_R + B_{R1} u_{R1} + B_R\ u_R\ + B_{R3} u_{R3} \quad \text{(B 2)}$$

where

$x_R = [\Delta\Psi_f\ \Delta\Psi_l\ \Delta\Psi_s\ \Delta\Psi_k\ ]$ $\qquad u_{R1} = [\Delta\delta\ \ \Delta\omega]^t$

$u_R = [\Delta v_f]$ $\qquad u_{R3} = [\Delta\ i_D\ \ \Delta\ i_Q]^t$

$$A_R = \begin{bmatrix} a_1 & a & 0 & 0 \\ a_3 & a_4 & 0 & 0 \\ 0 & 0 & a_5 & a_6 \\ 0 & 0 & a_7 & a_8 \end{bmatrix} \qquad B_{R1} = \begin{bmatrix} -b\, i_{f0} & 0 \\ -b_3 i_{f0} & 0 \\ b_5 i_{d0} & 0 \\ b_6 i_{l0} & 0 \end{bmatrix}$$

$$B_R = [b_1 \quad 0 \quad 0 \quad 0] \qquad B_{R3} = \begin{bmatrix} b\ \cos\delta_0 & -b\ \sin\delta_0 \\ b_3 \cos\delta_0 & -b_3 \sin\delta_0 \\ b_5 \sin\delta_0 & b_5 \cos\delta_0 \\ b_6 \sin\delta_0 & b_6 \cos\delta_0 \end{bmatrix}$$

$$i_{f0} = \cos\delta_0 i_{D0} - \sin\delta_0 i_{Q0}$$

$$i_{t0} = \sin\delta_0 i_{D0} + \cos\delta_0 i_{Q0}$$

Substituting eqn (2 9) in eqn (2 10) gives

$$I_D = c_1 \cos\delta\, \Psi_f + c\ \cos\delta\, \Psi_h + c_3 \sin\delta\, \Psi_g + c_4 \sin\delta\, \Psi_k$$

$$\text{(B 3)}$$

$$I_Q = -c_1 \sin\delta\, \Psi_f - c_2 \sin\delta\, \Psi_h + c_3 \cos\delta\, \Psi_g + c_4 \cos\delta\, \Psi_k$$

Differentiating eqn (2 9)

$$I_f = c_1 \Psi_f + c\ \Psi_f$$

$$I_t = c_3 \Psi_g + c_4 \Psi_k \qquad \text{(B 4)}$$

Eqn (2 10) is also differentiated to give

$$\begin{bmatrix} I_D \\ I_Q \end{bmatrix} = \begin{bmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} I_f \\ I_t \end{bmatrix} + \frac{d\delta}{dt} \begin{bmatrix} -\sin\delta & \cos\delta \\ -\cos\delta & -\sin\delta \end{bmatrix} \begin{bmatrix} I_f \\ I_t \end{bmatrix} \qquad \text{(B 5)}$$

The flux derivative terms in eqn (B 4) are replaced by their respective expressions obtained from the rotor state equations (B 2) I_f I_t so obtained are substituted in eqn (B 5) The resulting equation together with eqn (B 3) are now linearized to give the output equations of rotor circuit as

$$y_{R1} = C_{R1} x_R + D_{R1} u_{R1} \qquad \text{(B 6)}$$

$$y_R = C_R\ x_R + D_R\ u_{R1} + D_{R3} u_R + D_{R4} u_{R3} \qquad \text{(B 7)}$$

where $y_{R1} = [\Delta\ I_D \quad \Delta\ I_Q]'$ $y_R = [\Delta\ I_D \quad \Delta\ I_Q]'$

The **nonzero** elements of the different matrices are defined as

$C_{R1}(1\ 1) = c_1 \cos\delta_0$

$C_{R1}(1\ 2) = c_2 \cos\delta_0$

$C_{R1}(1\ 3) = c_3 \sin\delta_0$

$C_{R1}(1\ 4) = c_4 \sin\delta_0$

$C_{R1}(2\ 1) = -c_1 \sin\delta_0$

$C_{R1}(2\ 2) = -c_2 \sin\delta_0$

$C_{R1}(2\ 3) = c_3 \cos\delta_0$

$C_{R1}(2\ 4) = c_4 \cos\delta_0$

$C_{R2}(1\ 1) = (c_1 a_1 + c_2 a_3)\cos\delta_0$

$C_{R2}(1\ 2) = (c_1 a_2 + c_2 a_4)\cos\delta_0$

$C_{R2}(1\ 3) = (c_3 a_5 + c_4 a_7)\sin\delta_0$

$C_{R2}(1\ 4) = (c_3 a_6 + c_4 a_8)\sin\delta_0$

$C_{R2}(2\ 1) = -(c_1 a_1 + c_2 a_3)\sin\delta_0$

$C_{R2}(2\ 2) = -(c_1 a_2 + c_2 a_4)\sin\delta_0$

$C_{R2}(2\ 3) = (c_3 a_5 + c_4 a_7)\cos\delta_0$

$C_{R2}(2\ 4) = (c_3 a_6 + c_4 a_8)\cos\delta_0$

$D_{R1}(1\ 1) = I_{Q0}$

$D_{R1}(2\ 1) = -\ I_{D0}$

$D_{R2}(1\ 1) = -(c_1 b_2 + c_2 b_3)\, i_{q0} \cos\delta_0 + (c_3 b_5 + c_4 b_6 + c_5 b_4)\, i_{d0} \sin\delta_0$

$D_{R2}(1\ 2) = I_{Q0}$

$D_{R2}(2\ 1) = (c_1 b_2 + c_2 b_3)\, i_{q0} \sin\delta_0 + (c_3 b_5 + c_4 b_6 + c_5 b_4)\, i_{d0} \cos\delta_0$

$$D_R\ (2\ 2) = -I_{D0}$$

$$D_{R3}\ (1\ 1) = c_1 b_1 \cos\delta_0$$

$$D_{R3}\ (2\ 1) = -c_1 b_1 \sin\delta_0$$

$$D_{R4}\ (1\ 1) = (c_1 b + c\ b_3)\cos^2\delta_0 + (c_3 b + c_4 b_6)\sin\ \delta_0$$

$$D_{R4}\ (1\ 2) = -(c_1 b + c\ b_3)\sin\delta_0\cos\delta_0 + (c_3 b_5 + c_4 b_6)\sin\delta_0\cos\delta_0$$

$$D_{R4}\ (2\ 1) = -(c_1 b + c\ b_3)\sin\delta_0\cos\delta_0 + (c_3 b_5 + c_4 b_6)\sin\delta_0\cos\delta_0$$

$$D_{R4}\ (2\ 2) = (c_1 b + c\ b_3)\sin\ \delta_0 + (c_3 b_5 + c_4 b_6)\cos\ \delta_0$$

$$I_{D0} = \cos\delta_0 I_{d0} + \sin\delta_0 I_{q0}$$

$$I_{Q0} = -\sin\delta_0 I_{d0} + \cos\delta_0 I_{q0}$$

B 2 Mechanical System

The electromagnetic torque T acting on the generator rotor is given in [2] is expressed by

$$T_e = -x_d\ (i_d I_q - i_q I_d)$$

The currents i_d i_q and I_d I_q are transformed to D Q reference frame using the relationship given in eqn (2 7) It is noted that though eqn (2 7) is written specifically for transforming i_d i_q to D Q axis quantities the same relation also applies for the transformation of I_d I_q to corresponding currents in D Q frame of reference as

$$\begin{aligned} T_e = -x_d\ [&(\cos\delta\ i_D - \sin\delta\ i_Q)(\sin\delta\ I_D + \cos\delta\ I_Q) \\ &- (\sin\delta\ i_D + \cos\delta\ i_Q)(\cos\delta\ I_D - \sin\delta\ I_Q)] \end{aligned} \qquad (B\ 8)$$

Alternatively $I = -x_l (i_D I_Q - i_Q I_D)$ (B 9)

Substituting eqns (B 9) in eqn (2 17) and linearizing

$$\Delta\omega = -\frac{D\omega_0}{2H}\Delta\omega + \frac{\omega_0}{2H} x_l \, [I_{Q0}\Delta i_D + i_{D0}\Delta I_Q - I_{D0}\Delta i_Q - i_{Q0}\Delta I_D] \qquad \text{(B 10)}$$

combining this equation with eqn (2 16) results in the state equation of mechanical system is

$$x_M = A_M x_M + B_{M1} u_{M1} + B_M \, u_M \qquad \text{(B 11)}$$

where $x_M = [\Delta\delta \quad \Delta\omega]^t$

$u_{M1} = [\Delta I_D \quad \Delta I_Q]^t$ $\qquad$ $u_{M2} = [\Delta i_D \quad \Delta i_Q]^t$

The **nonzero** elements of various matrices are given by

$A_M(1\ 2) = 1 \qquad A_M(2\ 2) = -\dfrac{D\omega_0}{2H}$

$$B_{M1}(2\ 1) = \frac{\omega_0 x_d}{2H}(i_{d0}\sin\delta_0 - i_{q0}\cos\delta_0)$$

$$B_{M1}(2\ 2) = \frac{\omega_0 x_l}{2H}(i_{d0}\cos\delta_0 + i_{q0}\sin\delta_0)$$

$$B_{M2}(2\ 1) = \frac{\omega_0 x_l}{2H}(I_{q0}\cos\delta_0 - I_{d0}\sin\delta_0)$$

$$B_{M2}(2\ 2) = -\frac{\omega_0 x_l}{2H}(I_{q0}\sin\delta_0 + i_{d0}\cos\delta_0)$$

$x_l = \omega_0 L_l$

It is noted that as the mechanical power input is assumed to be constant

$\Delta I = 0$

The output equation of the mechanical system is given by

$$y_M = C_M x_M \tag{B 12}$$

where $y_M = [\Delta\delta \quad \Delta\omega]'$ $\qquad C_M = I$

B 3 Excitation System

Where Eqns (2 21 2 25) are linearized to give the state eqn of the excitation system as

$$\dot{x}_E = A_E x_E + B_{E1} u_{E1} + B_{E2} u_{E2} \tag{B 13}$$

where $x_E = [\Delta v_f \; \Delta v_r \; \Delta v \; \Delta v_{r1}]'$ $\qquad u_{E1} = \Delta v_s$ $\qquad u_{E2} = [\Delta\delta \quad \Delta\omega]'$

$$A_E = \begin{bmatrix} -\dfrac{K_E + S_E}{T_E} & 0 & \dfrac{1}{T_E} & 0 \\ -\dfrac{K_F(K_E + S_E)}{T_E T_F} & -\dfrac{1}{T_F} & \dfrac{K_F}{T_E T_F} & 0 \\ 0 & -\dfrac{K_A}{T_A} & -\dfrac{1}{T_A} & \dfrac{K_A}{T_A}(1-\dfrac{T_{PSS1}}{T_{PSS}}) \\ 0 & 0 & 0 & -\dfrac{1}{T_{PSS}} \end{bmatrix}$$

$$B_{E1} = \begin{bmatrix} 0 & 0 & -\dfrac{K_A}{T_A} & 0 \end{bmatrix}$$

$$B_{E2} = \begin{bmatrix} 0 & 0 & \dfrac{K_A}{T_A} K_{STAB} \dfrac{T_{PSS1}}{T_{PSS}} & \dfrac{K_{STAB}}{T_{PSS}} \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

The output equation is given as

$$y_t = C_t x_t \qquad \text{(B 14)}$$

$$y_t = \Delta v_t \qquad\qquad C_t = [1 \quad 0 \quad 0 \quad 0]$$

B 4 Network Model

The nonzero elements of matrices utilized in eqn (2 36) are given below

$$S_1(1\ 6) = \frac{1}{L_t}$$

$$S_1(2\ 2) = -\frac{R}{L} \qquad S_1(2\ 6) = -\frac{1}{L} \qquad S_1(2\ 7) = \frac{1}{L}$$

$$S_1(3\ 3) = -\frac{R}{L} \qquad S_1(3\ 7) = -\frac{1}{L} \qquad S_1(3\ 8) = \frac{1}{L}$$

$$S_1(4\ 4) = -\frac{R_1}{L_1} \qquad S_1(4\ 8) = \frac{1}{L_1}$$

$$S_1(5\ 6) = -\frac{1}{2L} \qquad S_1(5\ 8) = \frac{1}{2L}$$

$$S_1(6\ 1) = -\frac{1}{C} \qquad S_1(6\ 2) = \frac{1}{C} \qquad S_1(6\ 5) = \frac{1}{C}$$

$$S_1(7\ 2) = -\frac{1}{C_N} \qquad S_1(7\ 3) = \frac{1}{C_N}$$

$$S_1(8\ 3) = -\frac{1}{C} \qquad S_1(8\ 4) = -\frac{1}{C} \qquad S_1(8\ 5) = -\frac{1}{C}$$

$$S\ (7\ 1) = -\frac{1}{C_N} \qquad S_3(4\ 1) = -\frac{L_l}{L_1} \qquad S_4(1\ 1) = -\frac{1}{L_t} \qquad S_5(5\ 1) = -\frac{1}{2L}$$

The different matrices in the state equation of the network given by eqn (2 39) are defined as follows

$$A_N = \begin{bmatrix} S_1 & -\omega_0 I \\ \omega_0 I & S_1 \end{bmatrix} \quad , \quad B_{N1} = \begin{bmatrix} S & 0 \\ 0 & S \end{bmatrix}$$

$$B_N = \begin{bmatrix} 0 & \omega_0 S_3 \\ -\omega_0 S_3 & 0 \end{bmatrix} \quad , B_{N3} = \begin{bmatrix} S_3 & 0 \\ 0 & S_3 \end{bmatrix}, B_{N4} = \begin{bmatrix} S_5 & 0 \\ 0 & S_5 \end{bmatrix}$$

The expression for incremental magnitude of machine terminal voltage is now derived From Fig 2 6 the following equations can be written

$$v_{g\alpha} = v_{4\alpha} - L_{t1}\frac{di_\alpha}{dt} \tag{B 15}$$

$$v_{g\beta} = v_{4\beta} - L_{t1}\frac{di_\beta}{dt} \tag{B 16}$$

Transforming eqns (B 15 B 16) to D Q frame of reference using eqn (2 38) and linearizing the resulting equations gives

$$\begin{bmatrix} \Delta v_{gD} \\ \Delta v_{gQ} \end{bmatrix} = \begin{bmatrix} \Delta v_{4D} \\ \Delta v_{4Q} \end{bmatrix} + T_1 \begin{bmatrix} \Delta i_D \\ \Delta i_Q \end{bmatrix} - L_{t1} \begin{bmatrix} \Delta i_D \\ \Delta i_Q \end{bmatrix} \tag{B 17}$$

where $T_1 = \begin{bmatrix} 0 & -\omega_0 L_{t1} \\ \omega_0 L_{t1} & 0 \end{bmatrix}$

The generator terminal voltage v_g is expressed as

$$v_g = \sqrt{v_{gD} + v_{gQ}} \tag{B 18}$$

Linearizing eqn (B 18)

$$\Delta v_g = T \begin{bmatrix} \Delta v_{gD} \\ \Delta v_{gQ} \end{bmatrix} \tag{B 19}$$

where $T = \begin{bmatrix} \dfrac{v_{gD0}}{v_{g0}} & \dfrac{v_{gQ0}}{v_{g0}} \end{bmatrix}^t$

Substituting (B 17) in eqn (B 19)

$$\Delta v_s = T\begin{bmatrix}\Delta v_{4D}\\ \Delta v_{4Q}\end{bmatrix} + T\,T_1\begin{bmatrix}\Delta i_D\\ \Delta i_Q\end{bmatrix} - L_{tl}T\begin{bmatrix}\Delta i_D\\ \Delta i_Q\end{bmatrix} \tag{B.20}$$

The above equation is rewritten as

$$\Delta v_s = T_5 x_N + T_6 x_N \tag{B.21}$$

where $T_5 = T\,T_3 + T\,T_1 T_4$ $\qquad T_6 = -L_{tl} T\,T_4$

The nonzero elements of T_3 and T_4 are defined by

$T_3(1,8) = T_3(2,16) = 1.0$

$T_4(1,4) = T_4(2,12) = 1.0$

Substituting eqn. (2.39) in eqn. (B.21) results in the output equation of network model

$$y_{N1} = C_{N1}x_N + D_{N1}u_{N1} + D_N u_N + D_{N3}u_{N3} + D_{N4}u_{N4} \tag{B.22}$$

where $y_{N1} = \Delta v_s$ $\quad C_{N1} = T_5 + T_6 A_N$ $\quad D_{N1} = T_6 B_{N1}$

$D_N = T_6 B_N$ $\quad D_{N3} = T_6 B_{N3}$ $\quad D_{N4} = T_6 B_{N4}$

Four more output equations are written for the network model

$$y_N = C_{N2}x_N \tag{B.23}$$

$$y_{N3} = C_{N3}x_N \tag{B.24}$$

$$y_{N4} = C_{N4}x_N \tag{B.25}$$

$$y_{N5} = C_{N5}x_N \tag{B.26}$$

where $y_N = [\Delta i_D \quad \Delta i_Q]^t$ $\quad y_{N3} = [\Delta v_{3D} \quad \Delta v_{3Q}]$ $\quad y_{N4} = [\Delta i_D \quad \Delta i_Q]^t$

$y_{N5} = [\Delta i_{4D} \quad \Delta i_{4Q}]^t$ $\qquad C_N = T_4$

The nonzero elements of C_{N3} C_{N4} C_{N5} are defined by

$$C_{N3}(1,7) = C_{N3}(2,15) = 1.0$$

$$C_{N4}(1,5) = C_{N4}(2,13) = 1.0$$

$$C_{N5}(1,3) = C_{N5}(2,11) = 1.0$$

B.5 Static VAR System

The nonzero elements of the different matrices used in eqn (2.62) and eqn (2.63) are defined by

$$A_S(1,1) = -\frac{\omega_0}{Q} \qquad A_S(1,2) = -\omega_0 \qquad A_S(1,6) = \omega_0 v_{3D0}$$

$$A_S(2,1) = \omega_0 \qquad A_S(2,2) = -\frac{\omega_0}{Q} \qquad A_S(2,6) = \omega_0 v_{3Q0}$$

$$A_S(3,4) = -1.0 \qquad A_S(3,7) = 1 - \frac{T_1}{T}$$

$$A_S(4,1) = -\frac{K_D\, i_{3D0}}{T_M\, i_{30}} \qquad A_S(4,2) = -\frac{K_D\, i_{3Q0}}{T_M\, i_{30}} \qquad A_S(4,4) = -\frac{1}{T_M}$$

$$A_S(5,3) = -\frac{K_I}{T_S} \qquad A_S(5,4) = \frac{K_P}{T_S} \qquad A_S(5,5) = -\frac{1}{T_S}$$

$$A_S(5,7) = -\frac{K_P}{T_S}\left(1 - \frac{T_1}{T}\right) \qquad A_S(6,5) = \frac{1}{T_D} \qquad A_S(6,6) = -\frac{1}{T_D}$$

$$B_{S1}(1,1) = \omega_0 B_0 \qquad B_{S1}(2,2) = \omega_0 B_0$$

$$B_{S1}(4,1) = \frac{v_{3D0}}{v_{30} T_M} \qquad B_{S1}(4,2) = \frac{v_{3Q0}}{v_{30} T_M}$$

$$B_S(3\,1) = \frac{T}{T}\frac{1}{}K \frac{i_{4D0}}{i_{40}} \qquad B_S(3\,2) = \frac{T}{T}\frac{1}{}K \frac{i_{4Q0}}{i_{40}}$$

$$B_S(5\,1) = -\frac{K_I}{T_S}\frac{T}{T}\frac{1}{}K \frac{i_{4D0}}{i_{40}} \qquad B_S(5\,2) = -\frac{K_P}{T_S}\frac{T}{T}\frac{1}{}K \frac{i_{4Q0}}{i_{40}}$$

$$B_S(7\,1) = \frac{K}{T}\frac{i_{4D0}}{i_{40}} \qquad B_S(7\,2) = \frac{K}{T}\frac{i_{4Q0}}{i_{40}}$$

$$B_{S3}(3\,1) = 1\,0 \qquad B_{S3}(5\,1) = -\frac{K_I}{T_S}$$

$$C_S(1\,1) = C_S(2\,2) = 1\,0 \qquad D_S = 0$$

B 6 Thyristor Controlled Series Capacitor

B 6 1 Constant Angle Control

The nonzero elements of the different matrices used in eqn (2 79) and eqn (2 80) are defined by

$$A_{TCA}(1\,1) = -\frac{R_t}{L_t} \qquad A_{TCA}(1\,2) = \frac{1}{L_t} \qquad A_{TCA}(1\,3) = -\omega_0$$

$$A_{TCA}(1\,9) = -\frac{\omega_0}{(\omega_0 L_t\ )^2}(1-\omega_0^{\,2} L_t\ C_t\ )^2 v_{t\,D0} \qquad A_{TCA}(2\,1) = -\frac{1}{C} \qquad A_{TCA}(2\,4) = -\omega_0$$

$$A_{TCA}(3\,1) = \omega_0 \qquad A_{TCA}(3\,3) = -\frac{R_t}{L_t} \qquad A_{TCA}(3\,4) = \frac{1}{L}$$

$$A_{TCA}(3\,9) = -\frac{\omega_0}{(\omega_0 L_t\ )}(1-\omega_0\ L_t\ C_t\ )\ v_{\ Q0} \qquad A_{TCA}(4\,2) = \omega_0 \qquad A_{TCA}(4\,3) = -\frac{1}{C_t}$$

$$A_{TCA}(5\,2) = -\frac{v_{t\,D0}}{T_{\ t\ t}\ v_{t\,0} X_I} \qquad A_{TCA}(5\,4) = -\frac{v_{t\,Q0}}{T\ \ v_{t\,0} X_I} \qquad A_{TCA}(5\,5) = -\frac{1}{T}$$

$$A_{TCA}(6\,5) = -\frac{1}{T_{II}} \qquad A_{TCA}(6\,6) = -\frac{1}{T_{PI}} \qquad A_{TCA}(7\,5) = -K_I\ \frac{T_{PI1}}{T_{PL}}$$

$$A_{TCA}(7\,6) = K_{II}\ (1-\frac{T_{II1}}{T_{II}}) \qquad A_{TCA}(8\,5) = -\frac{K_P}{T_P}\frac{T_{PI1}}{T_{PI}} \qquad A_{TCA}(8\,6) = \frac{K_P}{T_P}(1-\frac{T_{IL1}}{T_{PI}})$$

$$A_{TCV}(8\ 8) = -\frac{1}{T_P} \qquad A_{TCV}(9\ 7) = \frac{1}{T_{TCSC}} \qquad A_{TCV}(9\ 8) = \frac{1}{T_{TCSC}}$$

$$A_{TCV}(9\ 9) = -\frac{1}{T_{TCSC}} \qquad B_{TCV1}(2\ 1) = \frac{1}{C} \qquad B_{TCV1}(4\ 2) = \frac{1}{C} \qquad B_{TCV1}(5\ 1) = \frac{i_{D0}}{T\ \ i_0}$$

$$B_{TCV1}(5\ 2) = \frac{i_{Q0}}{T\ \ i_0} \qquad B_{TCV}(6\ 1) = -\frac{1}{T_{II}} \qquad B_{TCV}(7\ 1) = K_I\ \frac{T_{PI1}}{T_{II}}$$

$$B_{TCV}(8\ 1) = \frac{K_P\ T_{PI1}}{T_P\ T_{PL}} \qquad C_{TCV}(1\ 2) = C_{TCV}(2\ 4) = 1\ 0$$

B 6 2 Constant Current Control

In The nonzero elements for this controller are same as those of Constant Angle controller except that in this case two changes have to be made and are given below

$$A_{TCC}(5\ 2) = 0 \qquad A_{TCC}(5\ 4) = 0$$

B 7 Interconnection of Various Subsystems

In this case the various vectors and matrices are defined as follows

$$x_T = [x_R \quad x_M \quad x_E \quad x_N \quad x_S \quad x_{TC}]$$

u_T = system input vector =

$$[u_{R1}\ u_{R2} \quad u_{R3} \quad u_{M1} \quad u_{M2} \quad u_{E1} \quad u_E \quad u_{N1} \quad u_N \quad u_{N3} \quad u_{N4} \quad u_{S1} \quad u_S \quad u_{TC}]'$$

y_T = system output vector =

$$[y_{R1} \quad y_R \quad y_M \quad y_E \quad y_{N1} \quad y_N \quad y_{N3} \quad y_{N4} \quad y_{S5} \quad y_S \quad y_{TC}]'$$

$$
F_T = \begin{bmatrix}
0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 \\
I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 \\
I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I \\
0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0
\end{bmatrix}
\quad
A_T = \begin{bmatrix}
A_R & 0 & 0 & 0 & 0 & 0 \\
0 & A_M & 0 & 0 & 0 & 0 \\
0 & 0 & A_F & 0 & 0 & 0 \\
0 & 0 & 0 & A_N & 0 & 0 \\
0 & 0 & 0 & 0 & A_S & 0 \\
0 & 0 & 0 & 0 & 0 & A_{TC1}
\end{bmatrix}
$$

$$
B_T = \begin{bmatrix}
B_{R1} & B_R & B_{R3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & B_{M1} & B_M & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & B_{F1} & B_F & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{N1} & B_N & B_{N3} & B_{N4} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{S1} & B_S & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{TC1}
\end{bmatrix}
$$

$$
C_T = \begin{bmatrix}
C_{R1} & 0 & 0 & 0 & 0 & 0 \\
C_R & 0 & 0 & 0 & 0 & 0 \\
0 & C_M & 0 & 0 & 0 & 0 \\
0 & 0 & C_F & 0 & 0 & 0 \\
0 & 0 & 0 & C_{N1} & 0 & 0 \\
0 & 0 & 0 & C_N & 0 & 0 \\
0 & 0 & 0 & C_{N3} & 0 & 0 \\
0 & 0 & 0 & C_{N4} & 0 & 0 \\
0 & 0 & 0 & C_{N5} & 0 & 0 \\
0 & 0 & 0 & 0 & C_S & 0 \\
0 & 0 & 0 & 0 & 0 & C_{TC1}
\end{bmatrix}
$$

$$
D_r = \begin{bmatrix}
D_{I1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
D_{I} & D_{R3} & D_{I3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{N1} & D_{N} & D_{N3} & D_{N4} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{S} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

APPENDIX C
SYSTEM DATA

System Base Quantities

Base Voltage = 400 kV

Base MVA = 100

Base Frequency = 50 Hz

Generator Data

Sn = 1110 MVA

V_n = 22 KV

Pf = 0 9

f_n = 50 Hz

Ra = 0 0036 pu

x_l=0 21 pu

R_0 = 0

X_0 = 0 195 pu

H = 3 22 sec

D = 0

T_{d0}=6 66 sec

T_{q0}=0 44 sec

T''_{d0}=0 032 sec

T''_{q0}=0 057 sec

x_d=1 933pu

x_q=1 743 pu

x_d=0 467 pu

x_q=1 144 pu

x_d=0 312pu

x_q=0 312pu

Transformer Data (on generator base)

$X_t = 0\ 15\ pu$

Transmission Line Data

Resistance (R)	= 0 055 Ω per phase per mile
Inductive Reactance (X_L)	= 0 52 Ω per phase per mile
Susceptance ($B_C = \frac{1}{X_C}$)	= 5 92 μ mho per phase per mile
Natural load	= 540 MW
Line length	= 600 Km

Excitation Syatem

v_t=1 pu

v_f=1 pu

V_{rmax}=9 75 pu

V_{rmin}= 7 pu

S_{Emax}=0 95

S_{Emin}=0

T_R=0 sec

K_A= 400 pu

T_A= 0 02 sec

K_E= 1 0 pu

T_E= 1 0 sec

K_F= 0 06 pu

T_F= 1 0 sec

Static Var Compensator

T_M=2 4 ms T_S=5 0 ms T_D= 1 667 ms

K_I = 1200 K_P = 1 K_D = 0 015 pu (3 %)

The parameters of Line Current auxiliary controller are given in the chapters 3 4 5

Thyristor Controlled Series Capacitor

Values of L_{tcr}, C_{tc} and R_{tcr} are chosen such that the line is series compensated by 11% of the line reactance

L_{tcr} = 0 000591682 H

C_{tc} = 0 2628097 F

R_{tcr} = 0 0001 pu

The parameters of CA and CC controllers are given in chapters 3 4 5

Power system stabilizer

The parameters of PSS are given in chapters 3 4 5

APPENDIX D

CALCULATION OF INITIAL CONDITIONS

D 1 Generator Initial Conditions

The vector diagram of the overall system is depicted in Fig E 1 The generator current I_g is given by

$$I_g = \frac{P_g - jQ_g}{V_g^*} \tag{E 1}$$

where V_g^* is the conjugate of generator terminal voltage V

The field voltage V_f and rotor angle δ are computed as follows

$$E_q = V_g + I_g(R + j x_q) \tag{E 2}$$

$$\delta = \angle E_q - \pi / 2 \tag{E 3}$$

$$V_f = |E_q| + I_{gd}(x_d - x_q) \tag{E 4}$$

where I_{gd} is the component of generator current along d axis

The initial values of other variables are

$$I_f = \frac{V_f}{x_{ff}} \tag{E 5}$$

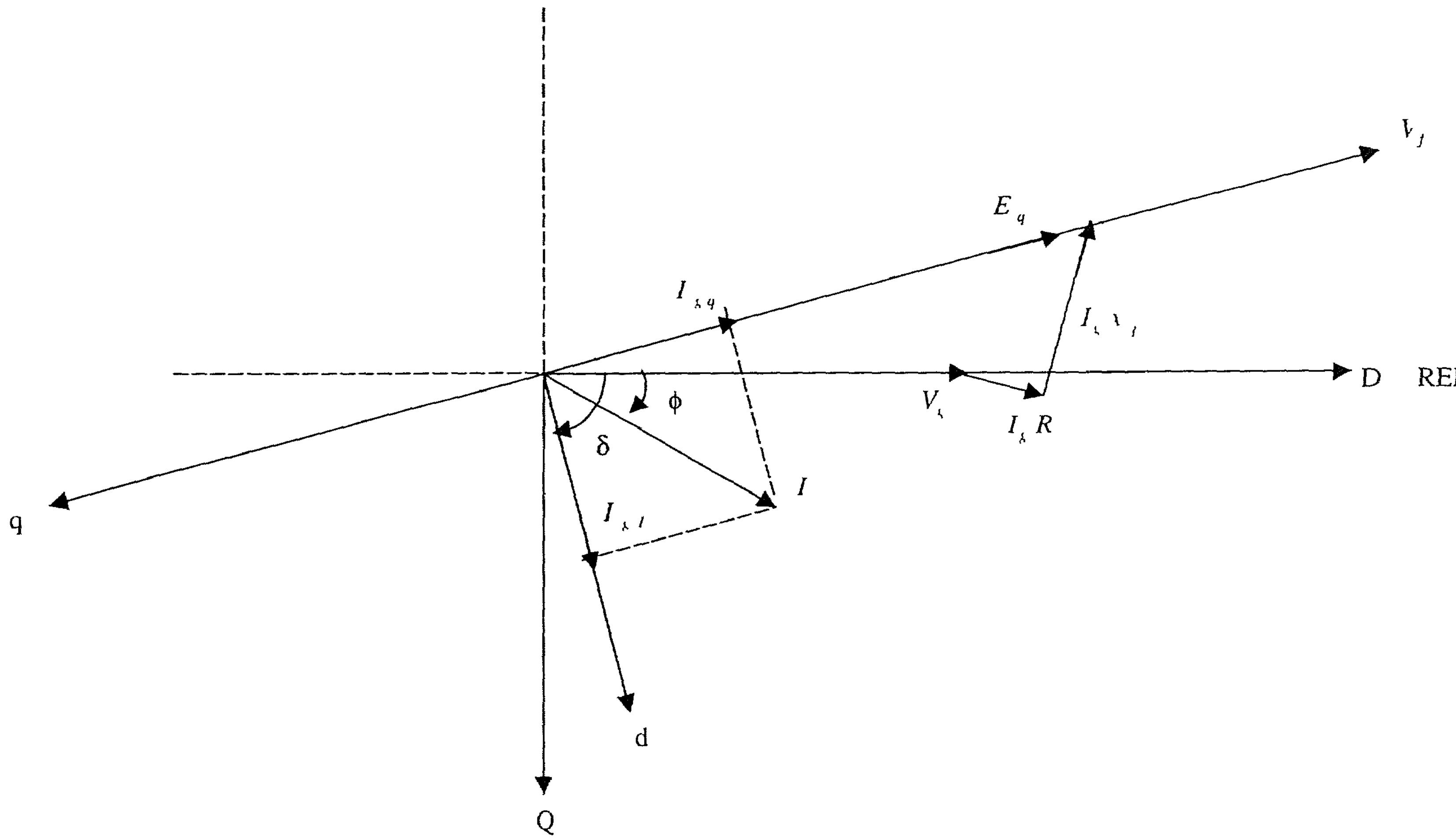


FIG E 1 VECTOR DIAGRAM OF SYSTEM IN STEADY STATE

REFERENCES

[1] R K Varma Control of Static Var Systems for Improvement of Dynamic Stability and Damping of Torsional Oscillations P hd Thesis IITK

[2] R S Ramshaw K R Padiyar Generalized System Model for Slipring Machines *IEE Proceedings* Vol 120 No 6 June 1973

[3] IEEE CIGRE FACTS Overview and FACTS Applications

[4] K R Padiyar and R S Ramshaw Dynamic Analysis of Multi machine Power Systems *IEEE Trans on PAS* Vol PAS 91 pp 526 535 Mar /Apr 1972

[5] K R Padiyar and R K chaurasia Analysis of Torsional Interactions With Thyristor Controlled Series Compensation (TCSC) Power System Conference Sep 97 Florida

[6] K R Padiyar M K Geetha K U Rao A Novel Power Flow Controller For Controlled Series Compensation IEE Conference London May 1996

[7] R L Hauth S A Miske and F Nozari The Role and Benefits of Static VAR Systems in High Voltage Power System Applications *IEEE Trans on PAS* 101 pp 3761 3770 Oct 1982

[8] K R Padiyar and R K Varma Damping Torque Analysis of Static VAR System Controllers *IEEE Transactions on Power Apparatus and Systems* Vol 6 No 2 May 1991

[9] K R Padiyar and R K Varma Static Var System Auxiliary Controllers for damping of Torsional Oscillations International Journal of Electric Power and Energy Systems Vol 12 No 4 pp 271 286 Oct 1990

[10] P M Anderson A A Fouad Power System Control and Stability *Iowa State University Press Iowa* 1977

[11] T J E Miller Reactive Power Control in Electric Systems *John wiley and Sons New York* 1982

[12] P Kundur Power System Stability and Control *New York McGraw Hill* 1994

[13] T Ohyama K Yamashita T Maeda H Suzuki and S Mine Effective Application of Static VAR Compensators to Damp Oscillations *IEEE Trans on PAS* Vol PAS 104 pp 1405 1410 June 1985

[14] Stevenson W D Elements of Power System Analysis 4^{th} edn MC Graw Hill New York 1982

[15] E Larsen C Bowler B Damsky S Nilsson Benefits of Thytistor Controlled Series compensation CIGRE Session 1992 5 Sept

[16] P S Dolan J R Smith and W A Mittelstadt A study of TCSC optimal damping control parameters for different operating conditions IEEE *Transactions on Power systems Vol 10 No 4 Nov 1995*

[17] K R Padiyar Dynamic stability of FACTS devices Application of FACTS Controllers IISc Bangalore 1998

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